Total Maximum Daily Load for Nutrients in Clear Lake, Lake County, California Technical Report

Final

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Prepared for:
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1 INTRODUCTION

Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's (USEPA's) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for waterbodies that are not meeting their designated uses even though pollutant sources have implemented technology-based controls. A TMDL establishes the allowable load of a pollutant or other quantifiable parameter based on the relationship between pollutant sources and in-stream water quality. A TMDL provides the scientific basis for a state to establish water quality-based controls to reduce pollution from both point and nonpoint sources and restore and maintain the quality of the state's water resources (USEPA, 1991).

The Central Valley Regional Water Quality Control Board (CVRWQCB) and USEPA have coordinated a watershed assessment and modeling study to support the calculation of a nutrient TMDL for Clear Lake, which is listed as impaired by nutrients on California's 1998 and 2002 section 303(d) lists based primarily on intense algal growth. This document presents the results of the study and provides the technical basis for the calculation of the TMDL.

1.1 Watershed Description

Clear Lake is the largest natural freshwater lake entirely within the borders of California. This eutrophic lake is relatively well-mixed by wind friction and thermal gradients throughout the year. The lake's nutrient richness supports large fish and wildlife populations, but causes frequent blooms of blue-green algae. Water quality data suggests a nitrogen-limited condition characterizes the summer periods when algal productivity is highest, and during the major bloom of 1990-1991. Watershed loading of phosphorus and subsequent accumulation as lakebed sediment provides a large source of phosphorus, causing this limitation. Studies have shown that the silts and clays in the lakebed sediment have been deposited at roughly the same rate as removal via faulting, maintaining the shallow lake feature since the Early Pleistocene age.

Clear Lake receives runoff from numerous river basins that discharge eroded sediments, nutrients, and trace elements. During heavy rain events, mainly during winter months, nutrients such as phosphorus sorbed to sediments are discharged by streams into the lake. Accumulated lakebed sediments provide a source of nutrients in addition to the suspended particles that increase turbidity. Wastewater and groundwater do not seem to contribute significantly to nutrient loading in Clear Lake (Richerson et al., 1994).

Nutrient enrichment problems have occurred in Clear Lake for several decades, particularly in the eastern portions of the system where algal mats accumulate as a result of dominant wind patterns. Sediments enter the lake carrying nutrients and trace elements due to both natural and anthropogenic causes. Introduction of these constituents increases the turbidity and algal biomass in the lake and ultimately decreases dissolved oxygen concentrations.

The proliferation of nuisance algal blooms in Clear Lake has generated significant public concern, not only due to the impact on water quality but the impact on the local economy. Historical records show evidence that this problem has begun in the last 50 years, citing the existence of bottom-dwelling algae and plant species that require ample lighting as late as the early 20^{th} century. Mats of blue-green algae, or cyanobacteria, have been substantial enough in the past to restrict boat passage and recreational access, and restrict growth of green algae, a type documented to flourish in Clear Lake as late as the 1920s. The odors and discoloration of Clear Lake as a result of blue-green algae mats covering thousands of square meters have also been shown by the California Department of Health Services to produce a mildly toxic environment for aquatic organisms and animals that drink the impacted waters.

An extreme algal bloom of *Microcystis* in Clear Lake from September to October 1990, covered tens of acres of the lake up to one meter thick. During this outbreak, residents left the area due to potent odors from methyl mercaptan, produced by the decaying mats. A large portion of Oaks Arm segment of Clear Lake and the channels in the Clear Lake Keys subdivision leading to Oaks Arm were too thickly clogged with matting to allow small boats to navigate. *Microcystis*, as well as the cyanobacteria species *Anabena*, typically form scums in the late summer to early fall, while the species *Aphanizomenon* commonly forms scums in the late spring and again in the fall. Clear Lake has also experienced blooms of *Aphanizomenon* during winter months. However, scum-forming algaes are generally out-competed by diatoms and non-scum forming species during the winter months. The economic impacts on the Clear Lake region due to summertime blooms have been significant, as shown by the work of Hinton (1972), and have led to studies to define the source of the problem. These problem sources are further discussed in Section 4.0.

1.2 Watershed Description

Clear Lake is located in the Coast Ranges of California about 80 miles north of San Francisco. It is part of the Sacramento River Basin. Clear Lake is eight miles wide at its widest point and nineteen miles long. The lake covers approximately 70 square miles, with approximately 100 miles of shoreline. The average depth of the lake is 27 feet, with a maximum depth of 60 feet. Water temperature in the lake averages 61 degrees Fahrenheit (^{o}F) and ranges from an average of 40 °F in the winter to an average of 76 °F in the summer.

Clear Lake has several tributaries as seen in Figure 1-1. These tributaries include Adobe Creek, Burns Valley Creek, Clover Creek, Cole Creek, Forbes Creek, Kelsey Creek, Manning Creek, Middle Creek, Molesworth Creek, Morrison Creek, Schindler Creek, and Scotts Creek. The combined drainage area is 441 square miles.

Land use in the watershed is primarily forested, shrubland, and grassland. Total urban area makes up less than 2.5 percent of the watershed. Table 1-1 lists the land uses in the Clear Lake watershed, their areas, and corresponding percents of the total watershed area (USGS, 2000).

Table 1-1. Land Use Categories and Areas

Land Use Category	Total Area (acres)	Percent of Total
Bare rock/sand/clay	966	0.34
Deciduous forest	110,029	39.00
Deciduous shrubland	48,390	17.15
Emergent herbaceous wetlands	90	0.03
Grassland/herbaceous	65,824	23.33
High intensity commercial/industrial/transportation	646	0.23
High intensity residential	2	<0.01
Low intensity residential	4,794	1.70
Mixed forest	23,053	8.17
Open water (not including Clear Lake)	1,491	0.53
Other grasses (urban/recreational; e.g. parks)	141	0.05
Pasture/hay	9,683	3.43
Planted/cultivated (orchards, vineyards, groves)	16,538	5.86
Quarries/strip mines/gravel pits	58	0.02
Row crops	6	<0.01
Small grains	1	<0.01
Transitional	429	0.15
Woody wetlands	1	<0.01
Total	**282,138**	**100.00**

The area around Clear Lake is geologically active as indicated by many hot springs in or near Clear Lake. Other geological features include a spring that produces carbonated water in the lake, a sulphur spring located on an island in the lake, and the 4,200 foot volcanic cone of Mount Konocti.

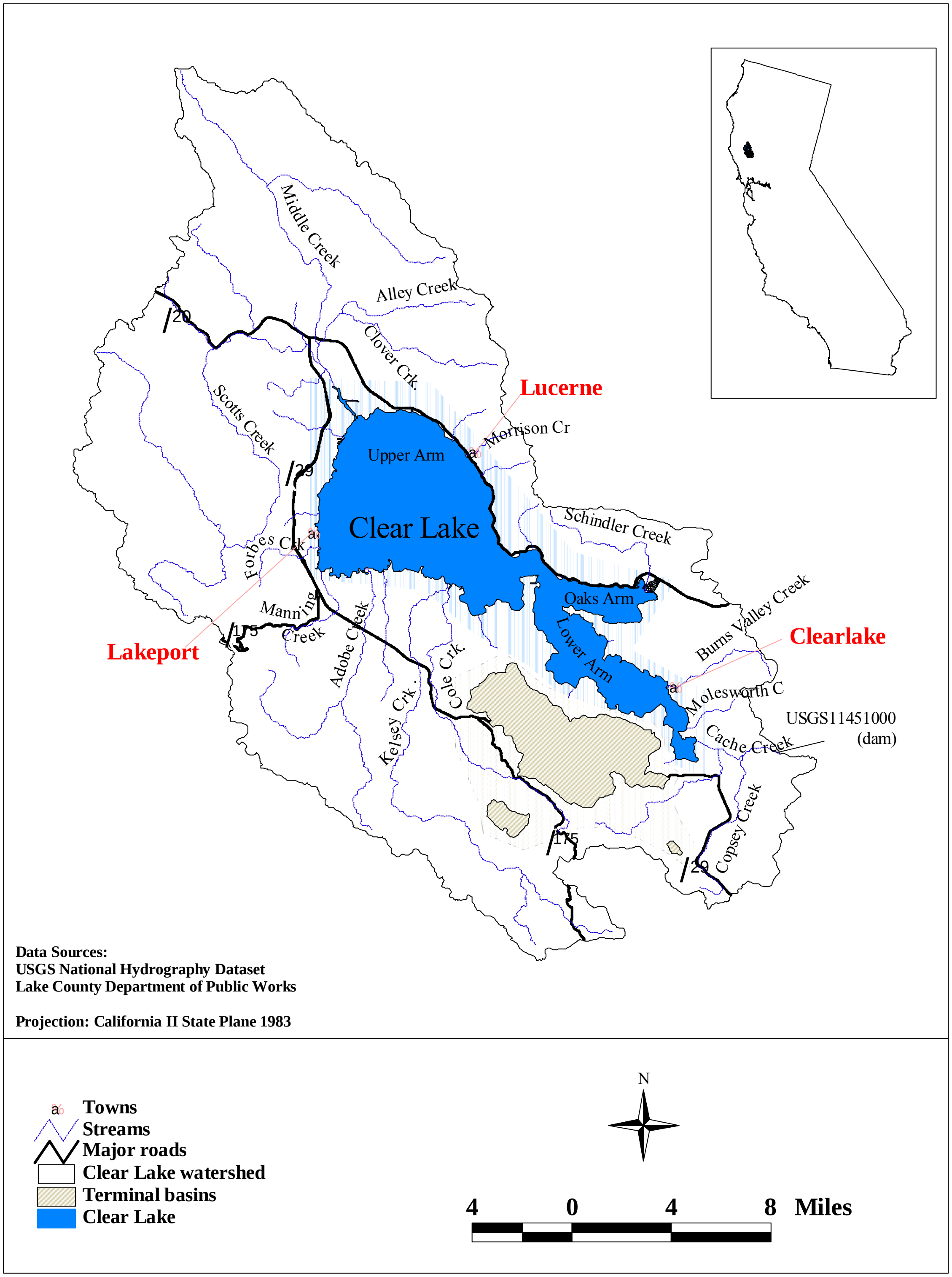


Figure 1-1. Clear Lake and the Surrounding Watershed.

2 APPLICABLE CALIFORNIA WATER QUALITY STANDARDS

2.1 Beneficial Uses and Water Quality Objectives

Under section 303(d) of the Clean Water Act, states are to conduct biennial assessments of waters not meeting water quality standards and develop lists of such impaired waters. Waters on these lists are prioritized and TMDLs are developed. TMDLs identify the maximum pollutant amount that can be discharged to a waterbody, through point and nonpoint sources, such that the receiving waterbody can still meet water quality objectives (WQOs), usually during critical conditions.

Clear Lake has been placed on California's 1998 and 2002 303(d) lists for nutrient impairments primarily due to intense algal productivity episodes such as those experienced during the summers of 1990 and 1991. Clear Lake is the only listed waterbody in the watershed. The *Sacramento River Basin and San Joaquin River Basin Water Quality Control Plan (Basin Plan) for the California Water Quality Control Board Central Valley Region* (SSJ Basin Plan) identifies beneficial uses and water quality objectives for Clear Lake as existing municipal water supply, agriculture (irrigation and stock watering), recreation (contact and noncontact), warm freshwater habitat, warm spawning, and wildlife habitat (CVRWQCB, 1994). The Basin Plan also identifies cold freshwater habitat as a potential beneficial use.

The SSJ Basin Plan has nutrient-related WQOs for warm freshwater habitat and spawning. The following water quality objectives define the nutrient-related standards in the SSJ Basin Plan:

- Biostimulatory substances: "Water shall not contain biostimulatory substances which promote aquatic growths in concentrations that cause nuisance or adversely affect beneficial uses."

2.2 Numeric Target Selection

Because only narrative WQOs exist for nutrients for Clear Lake, a numeric target was identified for use in TMDL calculation. The numeric target represents attainment of the narrative WQOs and supports the beneficial uses of Clear Lake as a recreational and warm water habitat and spawning area. The target specifically aims to reduce algal bloom intensity during extreme climatological conditions, such as those experienced during the 1990-91 bloom, to a productivity level that supports beneficial uses during typical years.

Although Clear Lake is a highly productive system capable of supporting excessive macrophyte and diatom populations, noxious, mat-forming blue-green algal blooms are indicative of the "worst" conditions for this impaired waterbody. The magnitude, timing, and dominant species of blue green algae blooms vary significantly from year to year in Clear Lake based on the DWR dataset, suggesting that a numeric target be developed based on site-specific historic observations. Years thought to exhibit "compliant" conditions in Clear Lake with respect to beneficial uses were identified based on water quality data and anecdotal evidence. "Compliant" years are years where the lake was merely green (due to blue green algae in the water column) during the summer but significant amounts of noxious blue green algal scum were not recorded. These "compliant" years were characterized by moderate to low abundance of blue-green algal productivity in Clear Lake, and they represented a range of wet and dry conditions, although not extreme (i.e no extended drought or flood periods).

Five consecutive years (1985-1989) were selected as "compliant" years, based on a reduced number of complaints regarding bloom-related issues. In addition, these years represent the period just prior to the blooms characterizing the impairment, eliminating confounding factors such as changes in land use distribution, stream channel destabilization activities, or hydromodifications that tend to influence water quality. January 1st, 1985 was selected as the beginning of the "compliant" time period in order to eliminate discrepancies in watershed characteristics versus earlier years. Due to reports of scum present in large quantities during the 1990-91 bloom (Clean Lakes Diagnostic/Feasibility Study, 1994), these years were not considered compliant. Therefore, the "compliant" period ends on December 31st, 1989.

A chlorophyll-a concentration of 73 μg/L, which represents the maximum of summer peak concentrations for "compliant" years, was assigned as the TMDL target (not to be exceeded during any year). Had the peak concentration of chlorophyll-a not exceeded 73 μg/L during the summers of 1990-1991, the year would have been considered "compliant" and Clear Lake's recreational, warm water habitat, and warm water spawning beneficial uses would have been protected.

The critical concentration of chlorophyll-a was estimated by the modeling system (discussed in Section 6) developed for calculating the TMDL. This system was used to evaluate trends in chlorophyll-a at seasonal, annual, and multi-year scales. The modeling system verified a nitrogen limited condition during the critical summer and fall periods (discussed in Section 3). Reduction of external phosphorus loading was the scenario employed to control the magnitude of simulated chlorophyll-a concentrations because; (1) nitrogen-fixing phytoplankton are able to produce 40% of the nitrogen load to Clear Lake from the atmosphere, so any reductions to the external nitrogen load will be compensated for, and (2) hypereutrophic levels of phosphorus (as high as 1.0 mg/L) exist in Clear Lake, illustrating that phosphorus is clearly in excess. These data are discussed further in Section 3.

A nutrient concentration or ratio was not used explicitly as a target since numerous additional factors (e.g meteorological conditions) are contributing, and these are not fully represented in the available datasets. Available monitoring data show some years that don't have blooms exhibit extremely high phosphorus loads (accompanied by high lake volumes, e.g 1993,1995) or low N-P ratios (1995). Additionally, some productive years exhibit no indicative elevation in P concentrations in the spring prior to summer blooms (e.g 1990, 1991). These observations suggest that productive conditions are amplified by algal productivity in a cyclical fashion, and that short-term antecedent nutrient availability has a minor influence relative to internal loading caused by biomass decay, reduced oxygen conditions and subsequent release of phosphorus from the sediments during the bloom. Thus, phosphorus loads from the watershed must be reduced to ultimately limit lakebed phosphorus loading during the summer season and to attain the chlorophyll-a target. Reduction in external phosphorus loading from the watershed is also the primary management plan in the 1994 Clean Lakes Feasibility Study for Clear Lake.

3 DATA INVENTORY AND ANALYSIS

Data from numerous sources were used to characterize the watershed and lake water quality conditions, identify nutrient sources, and support the calculation of TMDLs for the watersheds. No new data were collected in the field as part of this effort. The data analysis provided both confirmation of impairment status and an understanding of the conditions that result in impairments.

3.1 Data Inventory

The categories of data used in developing this TMDL include physiographic data that describe the physical conditions of the watershed, and environmental monitoring data that identify past and current conditions and support the identification of potential pollutant sources. Table 3-1 presents the various data types and data sources used in the development of this TMDL.

Table 3-1. Inventory of Data and Information Used for the Source Assessment of Nutrients.

Data Set	Type of Information	Data Source(s)
Watershed physiographic data	Stream network	USGS National Hydrogaphy Dataset (NHD) reach file;
	Land use	USGS MRLC (1992); USGS GIRAS (1995 digitized Lake County land use survey-DWR)
	Counties	USEPA BASINS
	Cities/populated places	USEPA BASINS, U.S. Census Bureau's Tiger Data
	Soils	USEPA BASINS (USDA-NRCS STATSGO)
	Watershed boundaries	USEPA BASINS (8-digit hydrologic cataloguing unit)
	Topographic and digital elevation models (DEMs)	USEPA BASINS; USGS
Environmental monitoring data	Water quality monitoring data	USEPA's STORET; California Department of Water Resources; Lake County Department of Public Works; Lake County Vector Control
	Lake elevations	USGS; Stations CKL (Clear Lake at Lakeport) and CLA (Clear Lake at Cache Creek)
	Streamflow data	USGS; Cache Creek near Lower Lake, DWR; Scotts Creek, Middle Creek, Kelsey Creek
Environmental monitoring data	Meteorological station locations	BASINS; National Oceanic and Atmospheric Administration - National Climatic Data Center (NOAA-NCDC); California Data Exchange Center (CDEC); University of California's Statewide Integrated Pest Management Program (UCIPM)

Additional data regarding the Clear Lake system were also obtained, including information regarding specific projects undertaken in Clear Lake. Numerous local agencies are involved in ongoing monitoring and research projects, the findings of which are summarized in several documents. Some of these summaries are based on dated material, and the data analysis for this project considered, but was not entirely based on, the findings stated in these reports. The following sections describe the key data sets used for TMDL development.

3.1.1 Water Quality Data

Water quality data assist in the analysis of conditions and quantification of potential source contributions and attenuation processes, and are ultimately a critical element in modeling the source-response linkage for TMDL development. The California Department of Water Resources has conducted water quality monitoring in the Clear Lake watershed since 1969. Although monitoring at many of the stations was discontinued in the late 1990s or earlier, the spatial coverage of data was sufficient for presenting a useful representation of water quality trends in the watershed. Long-term datasets, of more than 20 years, collected by the California Department of Water Resources (DWR) stations were used for chemical and algal productivity data in the lake. The Lake County Department of Public Works (LCDPW), and the Lake County Vector Control also provided data.

Data from the Upper Arm of Clear Lake station (CL1) were used to investigate nutrient processes and relationships between various datasets and algal productivity in detail. The Upper Arm of Clear Lake represents approximately 70 percent of the lake by surface area, and approximately 63 percent of the volume, and the majority of watershed loading to the lake discharges to the Upper Arm via Scotts Creek. The central location and proximity of the Upper Arm to significant watershed loading suggests that conditions at this location may represent the dominant portion of the lake's response to external, and likely internal, nutrient loading. It should be noted that the three arms (Upper, Lower, and Oaks Arms) have been shown to behave differently with respect to nutrient cycling. For example, during the blooms of 1990 and 1991, scum-forming algae accumulated in the lower arms of the lake due to strong west winds, and subsequently affected water quality in these arms differently than in the Upper Arm segment.

Data collection at the Upper Arm station began in 1969, ten years prior to CL3 and CL4, recording the effects of significant anthropogenic disturbances (i.e increased streambed gravel mining from 1970 through 1972 for the construction of Highway 29). In assessing the conditions causing blue-green algal blooms, data collected at CL3 and CL4 were analyzed to investigate the timing and severity of algal productivity relative to CL1.

Depth-specific data collected at CL1 were depth-averaged for investigative purposes and examined for the entire 1969 through 2000 period. Relationships between the nutrient forms, physical behavior of the lake and tributaries, meteorological conditions, and the three primary blue-green algal species of concern (*Microcystis*, *Aphinazominon*, and *Anabaena*) were investigated. Data collected since the Clean Lakes Report (Richerson et al., 1994), were then analyzed in the context of the overall dataset to assess recent trends relative to past conditions.

3.1.2 Waterbody Characteristics

The assessment of waterbody characteristics involved analyzing streamflow data and assessing physical information. This information was used to determine the volume and hydraulic features of waterbodies for determining assimilative capacity and physical processes that affect nutrient transport for TMDL analysis. Long-term datasets that were collected by the California DWR were used for physical data in the lake. Monitoring data were also provided by the LCDPW.

3.1.3 Meteorological Data

Meteorological data was obtained from the California Data Exchange Center (CDEC), and from the University of California's Statewide Integrated Pest Management Program (UCIPM). These entities maintain online databases that were queried to obtain precipitation and air temperature data. The data obtained as a result of the queries was subjected to a QA/QC regime that identified gaps in data and unreasonable values that may misrepresent observed conditions. Missing and unreasonable values were encountered frequently in the precipitation and temperature datasets. Missing values were patched using a patching program that fills missing values with data from surrounding stations, and unreasonable values were deleted to allow for patching. The patched meteorological data were subsequently formatted for use in the modeling effort.

3.1.4 Land Characteristics Data

Geographical and land characteristic data contain information such as land use and soils coverages, as well as the locations of water quality monitoring stations, point source facilities, and weather stations. All of these data are necessary to georeference key information for the watershed and reservoir and identify key factors/sources contributing to water quality impairments in the reservoir. A significant quantity of geographic data for Clear Lake and the surrounding watershed were provided by the LCDPW.

Available land use data to support this study include the 1992 USGS Multi-Resolution Land Characteristic (MRLC) data, which are available for the entire study area. Land use data was also available from the Land and Water Use Survey for Lake County, California, which was provided by LCDPW. Soils data was obtained from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) SSURGO database. These data were reprojected into the State Plane California II coordinate system by LCDPW.

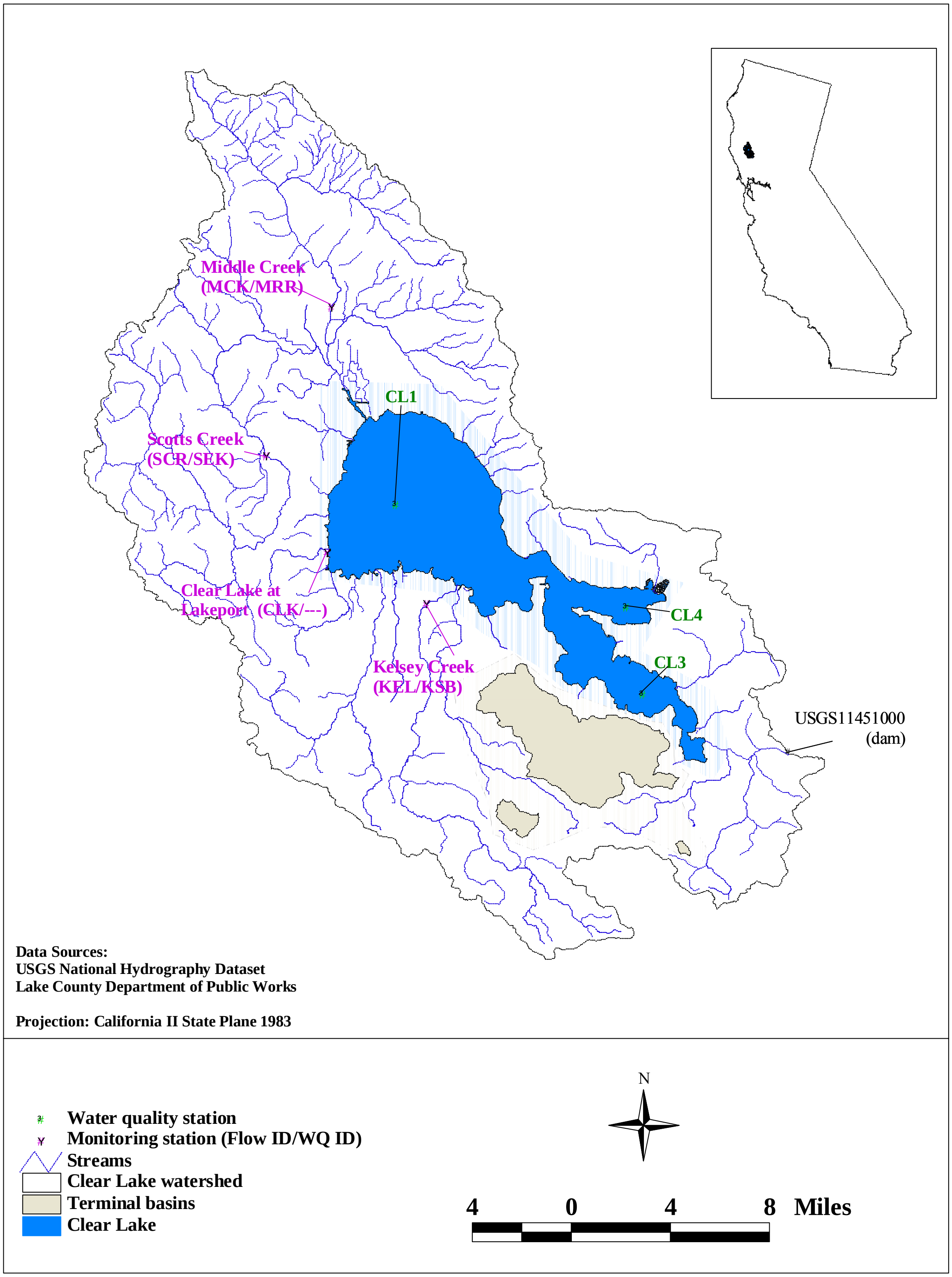
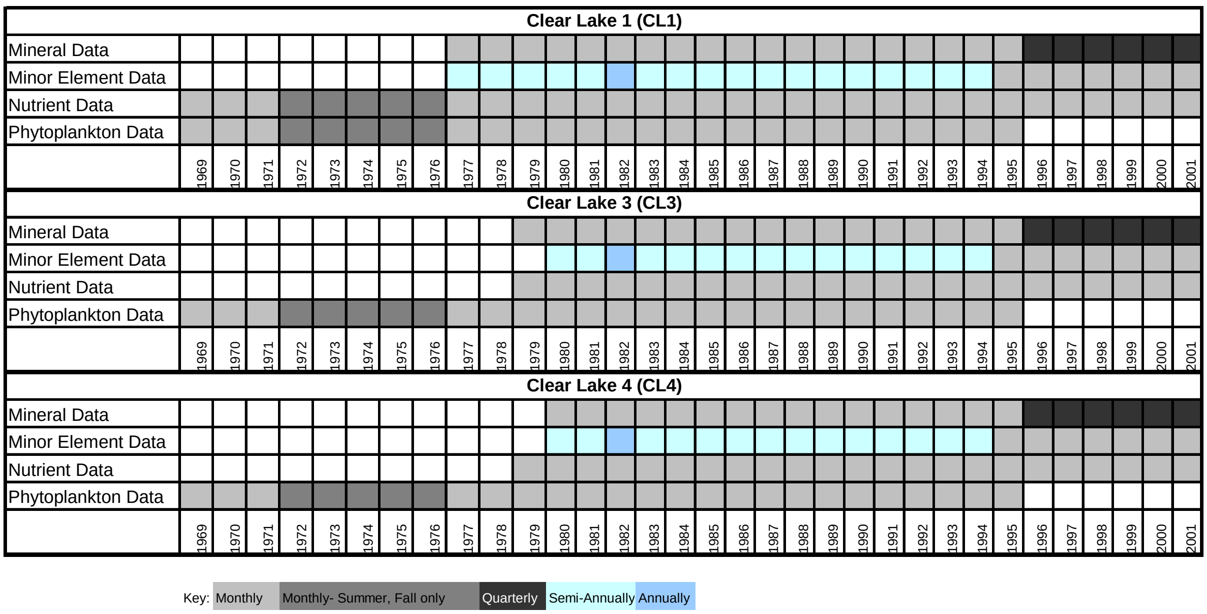


Figure 3-1. Clear Lake watershed and monitoring stations.

3.2 Data Analysis Summary

Meteorological data, tributary and lake water quality data, and physical parameter data collected at Clear Lake were analyzed to investigate the causes of excessive algal productivity and its subsequent inclusion on California's 1998 303(d) list of water bodies for nutrient impairment. Watershed monitoring stations that provide both water quality and flow data are located on Scotts Creek, Middle Creek, and Kelsey Creek. Locations of these monitoring stations are considered in the data analysis and are shown in Figure 3-1.

Table 3-2. Data availability and monitoring period for Stations CL1, CL3, and CL4.



Long-term datasets collected by the California Department of Water Resources (DWR) at the Upper Arm (CL1), Lower Arm (CL3), and the Oaks Arm (CL4) lake stations are shown in Table 3-2 and provide chemical, physical, and algal productivity data in the lake.

Two multi-year droughts (1975 through 1977 and 1987 through 1992) occurred in the Clear Lake region between 1969 and 2000, which is the period of available data. Annual rainfall totals in Lakeport during the 1987-1992 period were 17.2", 22.9", 31.2", 21.2", 23.5", and 26.9", respectively; all below the annual average of 33.5" based on 30 years of record. Although algal productivity in Clear Lake is high during non-drought conditions, the occurrence of intense blooms during these drought periods, especially the recent 1990 bloom, support the argument that drought periods facilitate intense algal blooms. Figure 3-2 shows in-lake phytoplankton populations at station CL1 for the 1969-1995 period. Note that units of population (#/mL) are used instead of units of mass. Mass data were not available for the data analysis, and phytoplankton populations may vary in mass by as much as six orders of magnitude. Therefore, the blooms of 1990 and 1991 are not discernable in this figure.

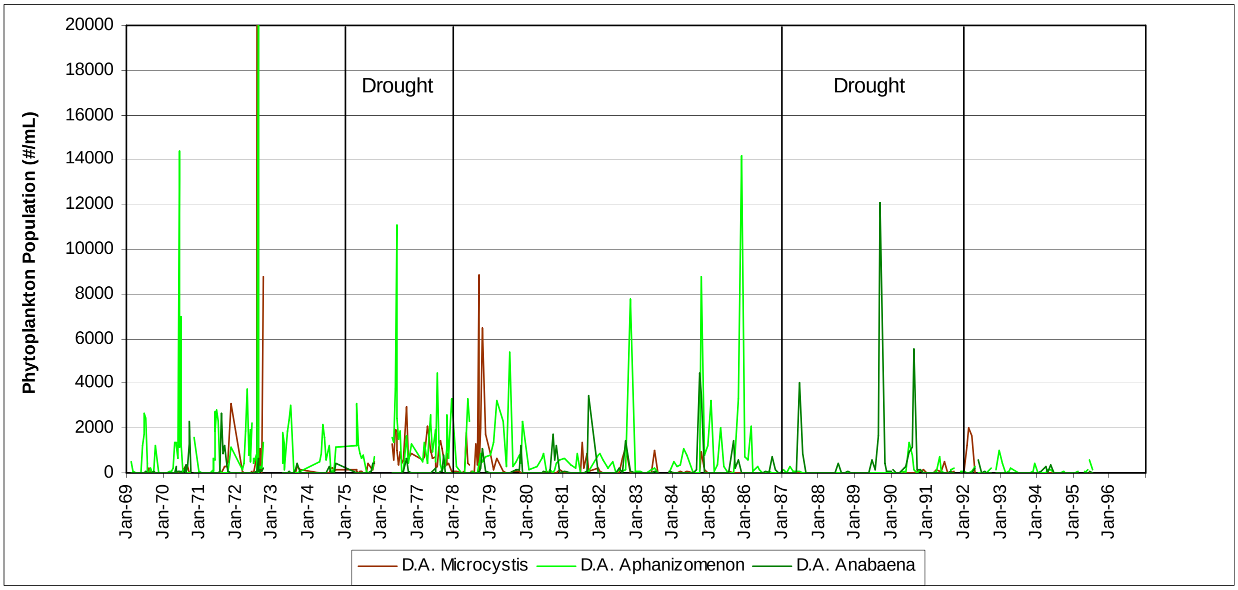


Figure 3-2. Microcystis, Aphanizomenon, and Anabaena Populations at Station CL1 for the Period of 1969-1995.

Several noticeable trends are evident in data collected since the 1994 Clean Lakes report (Richerson, et al., 1994), published just following a 5-year drought. Based on precipitation data recorded since that time, it is apparent that relatively wet conditions have continually existed at Clear Lake since 1993 (Figure 3-3). This recent wet period can be examined in context with other post-drought wet periods, such as that following the 1975 through 1977 drought when algal productivity declined similarly. Algal blooms have become less of an issue in the lake in the years since the end of the last drought in 1992, and multiple regression analyses suggest that climate is the influential factor in recent improvements in the lake's condition. These analyses are discussed later in this section.

Figure 3-4 shows 30 years of annual average secchi depths, total phosphorus, and orthophosphorus observed at station CL1 in the Upper Arm and the two multi-year droughts (1975-77 and 1987-92) are also identified. The secchi depth is a rough measure of clarity; it is the depth at which a secchi disk [a disk approximately 10 to 12 inches in diameter and covered by a black and white pattern] can no longer be seen. Figure 3-4 does not show a direct relationship between water clarity and drought status, based on an annual average of monthly samples. However, a trend showing an increase in secchi depths began in 1990 and has continued to increase until 2000, the last year of data. Increases in secchi depths were also observed in the Oaks and Lower Arms during the 1987 through 1992 drought. These improvements in water clarity will be discussed later in the summary.

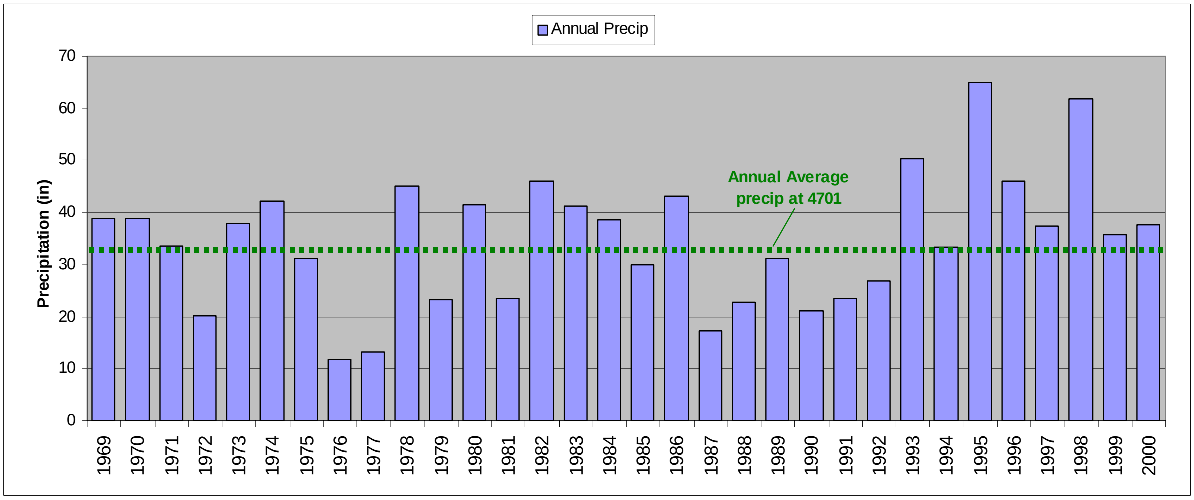


Figure 3-3. Annual Precipitation at the Lakeport gage.

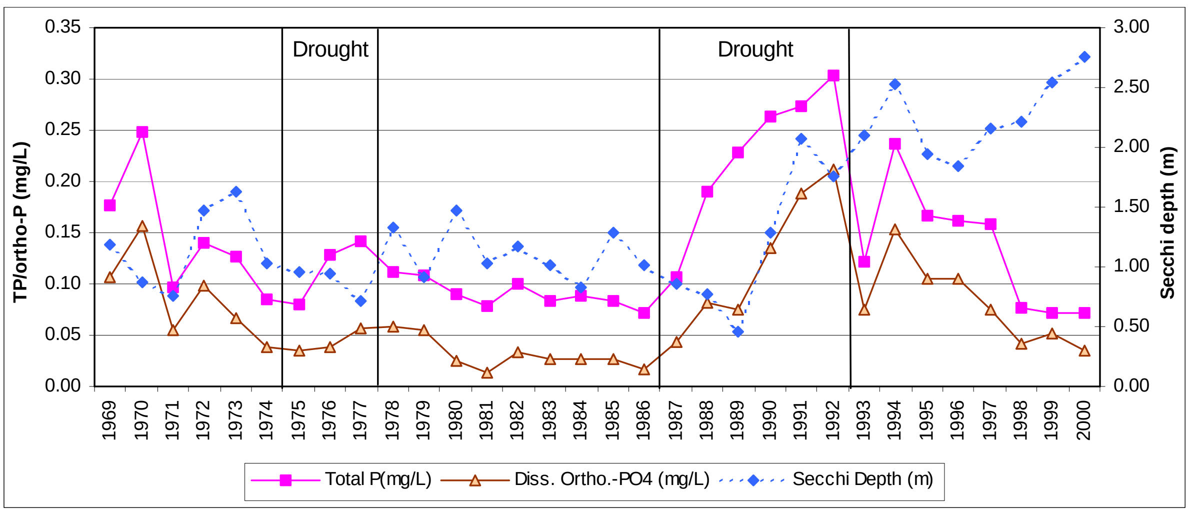


Figure 3-4. Annual average secchi depths, total phosphorus concentrations, and orthophosphorus concentrations at station CL1.

Examination of nitrogen to phosphorus (N:P) ratios also suggest a nitrogen-limited environment during the summer months, or the period characteristic of algal blooms in Clear Lake. Figure 3-5 illustrates monthly average N:P ratios and highlights the nitrogen and phosphorus limiting thresholds. The average January through June period exhibits non-limiting conditions with respect to both nitrogen and phosphorus, but the range of values also show that both nitrogen and phosphorus limitation has occurred during these months over the 1969-1995 period. More importantly, the critical period of July through December exhibits N:P ratios averaging in the nitrogen-limiting range. The month of August, in particular, has always exhibited nitrogen-limiting conditions. As a result of the nitrogen limitation during these critical months for algal productivity, phosphorus is considered to be in excess in Clear Lake.

Although the nitrogen-phosphorus relationship is an important aspect in limnology, a major source of nitrogen to Clear Lake (in excess of 40%) is nitrogen-fixing species of phytoplankton, which may produce an environment that is saturated with both phosphorus and nitrogen. Under these conditions, the uptake of these nutrients is not limited by the availability of either of these nutrients, and the traditional nitrogen-phosphorus ratio analyses become less useful. Therefore, detailed data analyses focus on phosphorus in the Clear Lake system.

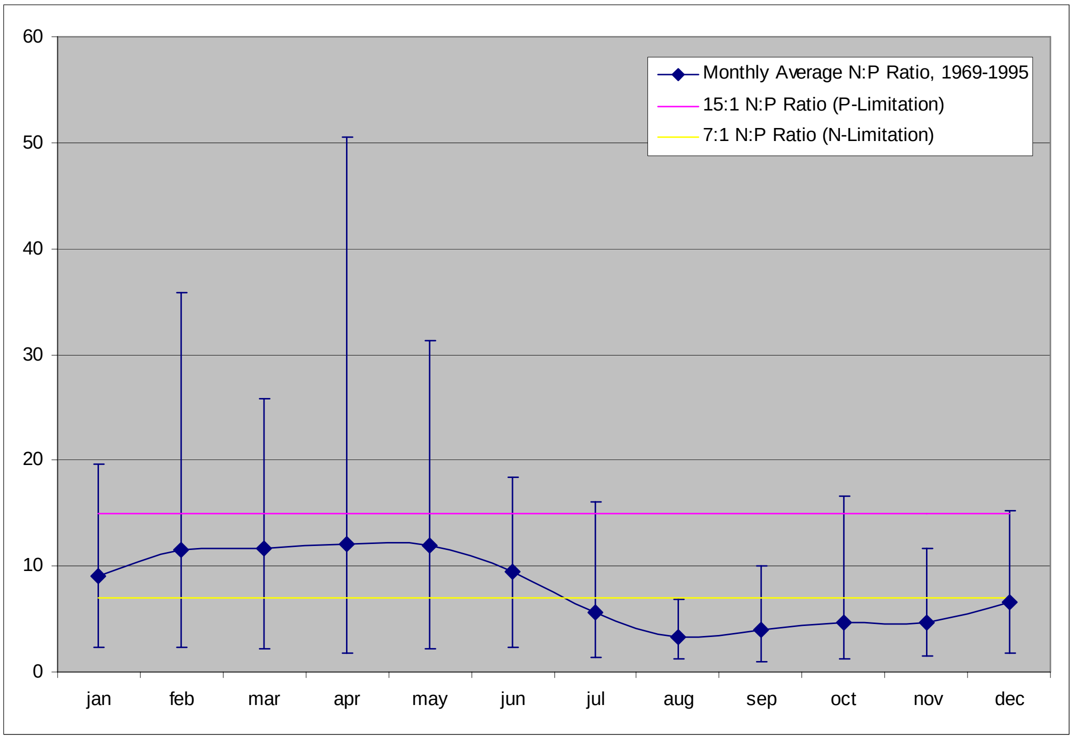


Figure 3-5. Monthly Averages and range of N:P Ratios, 1969-1995.

CL1 shows the highest concentrations of total and dissolved phosphorus of the three lake stations, and the highest instantaneous concentration of phosphorus (P) observed at station CL1 since 1970 occurred during the bloom of 1990 (8/23/1990: 1.0 mg/L at surface, 0.77 mg/L depth-averaged). A strong trend can be observed in the orthophosphorus (PO4) and thus total phosphorus (TP) data that show increases during drought periods and especially during the second drought at station CL1 (Figure 3-4). These drought-associated increases in TP and PO4 are consistently followed by a gradual decline during post-drought years. Although high annual average PO4 and TP concentrations occur during non-drought years (e.g 1970, 1994), long-term trends are evident in Figure 3-4 when defined by drought and non-drought conditions.

As shown in Figure 3-4, a decline in phosphorus from 1969 to the beginning of the 1975-1977 drought can be seen, followed by an increase over the drought years. The same trends occur during the remaining period of record; the non-drought period from 1978 to 1986 is characterized by a gradual decline in phosphorus, which increases substantially during the 1987 to 1992 drought period. Similarly to the post-1977 non-drought period, TP and PO4 concentrations decrease during the post-1992 non-drought period.

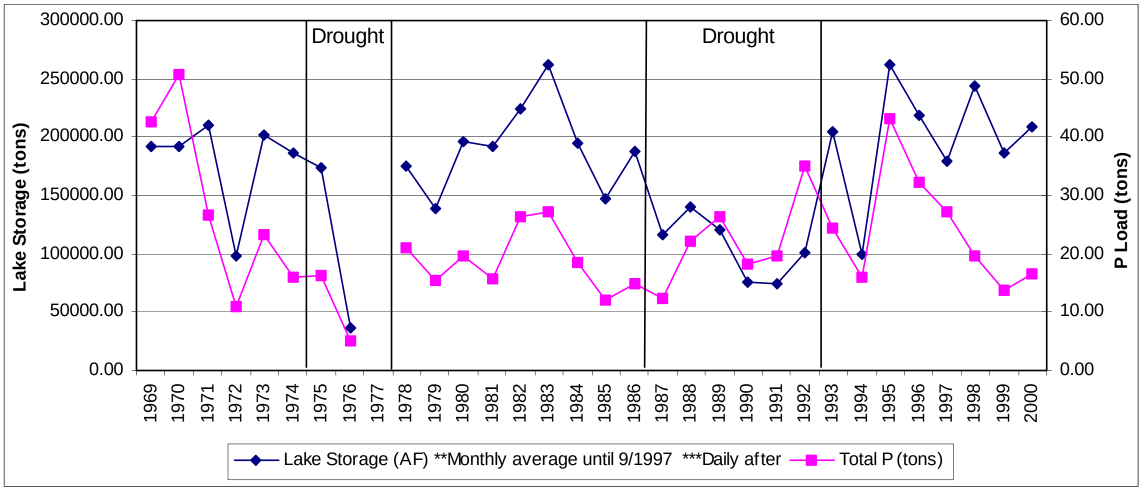


Figure 3-6. Annual average lake storage and total phosphorus mass at station CL1.

In-lake P loads, estimated using phosphorus concentrations at CL1 and coincident lake volume data, were investigated to estimate the effect of decreased lake volume during drought periods. Although the TP load (Figure 3-6) could not be calculated for the 1975-1977 drought period (due to data values of zero), increases in the total phosphorus load occurred over the duration of the 1987-1992 drought despite a gradual decline in lake volume. During these periods, increases in orthophosphorus relative to TP suggest that internal, rather than external loading, is the dominant source of P during recorded drought periods. Internal loading of dissolved orthophosphorus occurs in an environment of low dissolved oxygen, in most cases caused by decaying biomass on the lakebed. This suggests that internal loading of P merely amplified the bloom following an initial critical condition. Although internal loading amplified the blooms of 1990-91, the initial condition that started the bloom was a product of meteorological influences, which are further discussed below.

This critical condition for algal productivity was further investigated using watershed, in-lake, and meteorological monitoring data collected over the 1969-2000 time period. A multiple regression analysis was performed to identify relationships between meteorological and watershed processes and total phosphorus loads in Clear Lake. Based on the results of these analyses, there is no detectable overall trend in phosphorus loading during the period (1969-2000), but rather a weak trend of increasing phosphorus concentrations and loads during drought periods, and declining loads and concentrations during non-drought periods. This suggests that the reduction in TP concentration in 1995-2000 (a non-drought period) is due primarily to dilution, corresponding to wettest years and highest lake levels on record.

Although no trends in phosphorus loading are apparent over the 1969-2000 time period, in-lake TP loads declined during all three non-drought periods (1969-1974, 1978-1986, and 1993-2000). In addition, the years prior to the two droughts (1974 and 1986) and 2000 (the last year of available data) are similar in both lake storage and TP load. Recent erosion control measures implemented in the watershed may also be partially responsible for reductions of the in-lake phosphorus load, but the lake's external phosphorus load is small compared to internal phosphorus load from existing lake sediment, and variations in external load are likely masked by dilution of internal loads.

Further analyses were performed to investigate short-term trends in phosphorus loading in Clear Lake. The total phosphorus load is found to be associated with lake level (storage) and rainfall (sum of previous 4 months multiple regression; r2= 0.43) only. Both relationships are inverse, and there is no detection of runoff loading, indicating dilution has a dominant influence. To support this hypothesis, watershed loading data based on the Scotts Creek station were investigated to estimate the significance of watershed loading on in-lake water quality. Regression analyses between watershed data collected at Scotts Creek (Scotts Creek contributes approximately 30% of the total load of sediments to Clear Lake) and station CL1 in the upper arm of Clear Lake do not suggest a strong relationship between watershed loading and in-lake water quality. Although the relationship was not found to be strong, total phosphorus shows an inverse relationship with watershed inflow. This supports the theory that dilution has a dominant influence in Clear Lake, and that in-lake internal loading of P declines during periods of higher watershed inflow and lake levels. Details on the regression analyses are presented in Appendix E.

Microcystis, *Anabena*, and *Aphamizomenon* concentrations at station CL1 were examined in context with nutrient, minor element, and physical data from lake station CL1. Three sets of regressions were performed between blue-green algal data and various nutrient series collected at lake station CL1, including data collected during all years of record, data collected during the five wettest years (1981, 1982, 1983, 1993, 1995), and from the five driest years (1984, 1985, 1988, 1989, 1990). The R-squared results of the comparisons are shown in Figure 3-7.

Of the nutrient series, the strongest correlation (positive) exists between *Anabaena* and Total Kjeldhal Nitrogen (TKN). This relationship exists regardless of drought status. A multiple regression analysis also showed this relationship, but this is an association, not cause and effect. Horne et al (1972) concluded that > 40% of total N load in Clear Lake was from N fixation by blue-greens, adding to evidence that nitrogen is the limiting nutrient in the Clear Lake system. If nitrogen is the limiting nutrient during most summers and during the 1990 *Microcystis* bloom (during which, TKN was at the highest concentrations), this suggests that enough phosphorus is present not to limit algal productivity, and is in excess amounts in Clear Lake. The fact that excess phosphorus exists in Clear Lake is also illustrated in the monitoring data, which show hypereutrophic TP concentrations commonly exceeding 75ug/L, including a concentration of 100ug/L during the bloom of 1990.

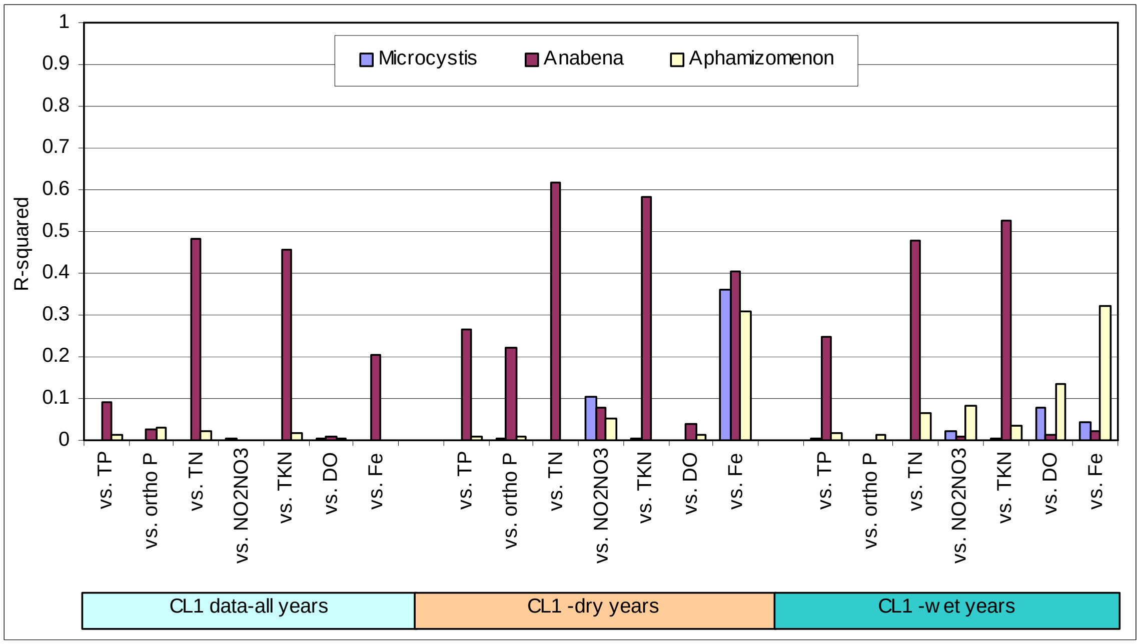


Figure 3-7. Results of linear regression analyses performed between blue-green algae and nutrient concentrations at station CL1.

Iron has been identified in the 1994 Clean Lakes Report as limiting in nitrogen fixation, but the degree to which iron cycling is significant in Clear Lake is difficult to establish based on available data since only biannual sampling (in the spring and fall) occurred during 1977 through 1994 and monthly samples were taken in 1995, 1999, and 2000. Although sampling data is sparse, a weak positive relationship (see Appendix E) also exists between iron and all three blue-green algal species during the five driest years, suggesting that iron, at times, may be limiting to blue-green algal productivity. Iron is associated with native watershed soils, and is introduced to the lake via erosion of these soils. Anthropogenic sources of iron (other than amplified erosion due to mining/construction practices) are unknown.

Based on a review of the available data and literature, a working hypothesis was developed as to the cause of blooms at Clear Lake. In a general context, Clear Lake is naturally eutrophic from high P levels in the volcanic soils and sediment of the watershed. USGS coring data suggest this has been the case for the last 15,000 years, although the relative productivity between green and blue-green algae was not ascertained by Bradbury (1988). Historical accounts, however, suggest that Clear Lake was dominated by macrophytes until surface mining and construction in the 1920s and 30's released mineral turbidity. These events shaded the macrophytes, while floating plankton could still utilize sunlight at the surface, and came to dominate. Although no water quality data exists from the 1920 or 1930s aside from historical accounts, similar increases in turbidity can be observed in the water quality record in the early 1970s. Although mineral turbidity may be reduced today and macrophyte populations have risen, future blue-green blooms may occur.

In conclusion:

- Clear Lake is naturally eutrophic. Anthropogenic impacts have exacerbated this condition and led to nuisance blue green algae blooms. There is evidence that Clear Lake is N-limited during summer and fall seasons when blue-green algae blooms occur.

- There is evidence that internal loads of P are a larger source than external loads on an annual basis.

- Drought conditions experience higher than normal TP concentrations because of less dilution of internal loading. Once this critical condition is met, internal loads are further amplified during drought periods because decaying matter contributes to low oxygen conditions in the sediment which trigger release of P bound to sediments.

- The data suggest that watershed inputs and meteorological conditions do not have an immediate effect (within a season) on lake clarity or blue-green algal productivity.

- Recent improvements in lake clarity and reductions in TP concentrations may be attributed to the effects of dilution due to higher than normal rainfall between 1995-2000.

- Many erosion control measures were implemented during the recent wet period, but the degree to which these measures have improved water quality versus the wet climate is unclear.

4 LINKAGE ANALYSIS

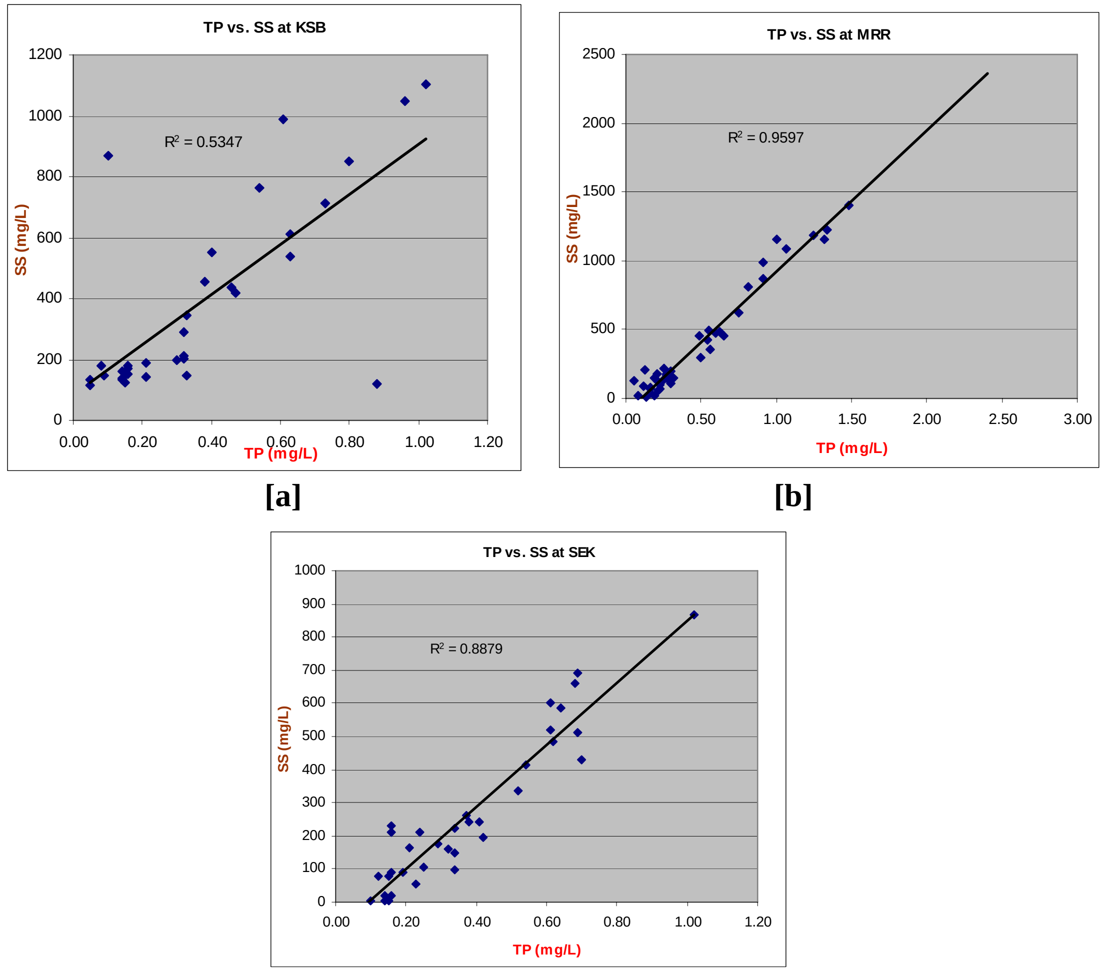
4.1 Source Analysis

Prior research and a review of recent data conducted for this TMDL suggests that nuisance blue-green algae blooms are facilitated by high phosphorus loading to the lake. In addition to the occurrence of hypereutrophic levels of phosphorus (summer peak concentrations frequently exceed 0.5 mg/L), a correlation between high in-lake phosphorus concentrations due to internal loading and algal productivity has been identified and discussed in the Data Analysis. For reasons cited in the Data Analysis Summary, the source analysis will focus on phosphorus in the Clear Lake system.

Particulate and dissolved components of phosphorus are transported from the watershed and discharged to Clear Lake. High in-lake orthophosphorus concentrations during relatively dry years suggests that this discharge of bioavailable phosphorus to the lake does not have an immediate effect, but rather, phosphorus-laden sediment settling to the lakebed is ultimately the largest source of phosphorus for Clear Lake. These phosphorus-laden lakebed sediments accumulate over years of tributary contributions and become a significant source of orthophosphorus during low dissolved oxygen conditions, which promote conversion of particulate to dissolved phosphorus. Although lakebed sediments have historically been a major source of phosphorus and were the primary source during the blooms of 1990-1991, phosphorus-laden sediments in the lakebed originate in the watershed and are discharged to the lake at a rate of approximately 160 metric tons of phosphorus per year (Lake County/UCD Clean Lakes Project: Final Report, July 1994).

Lake County data show a strong correlation between in- stream total phosphorus and suspended solids (Figure 4-1), supporting the idea that much of the phosphorus in Clear Lake is initially delivered with eroded sediments, caused by both natural and anthropogenic processes. Anthropogenic sources of phosphorus or sediment-associated phosphorus in the Clear Lake watershed include lands affected by controlled burning, timber harvesting and associated logging road construction, cattle and sheep grazing, shoreline dredging and filling, surface mining of various types of deposits, land use change (primarily wetlands loss), and sewage and septic overflows.

The more significant sources of sediment are thought to be surface mining of active streambeds for gravel and unpaved logging roads, particularly in areas of disturbance in the steeply sloped portions of the watershed (Lake County/UCD Clean Lakes Project: Final Report, July 1994). Goldstein and Tolsdorf (1994) estimated that channel erosion produces 34 percent and road cuts produce 13 percent of eroded sediments from the Clear Lake watershed. Goldstein and Tolsdorf (1994) estimate some of the lesser contributions from wildfire erosion (4%) and general construction in the watershed (4%). Other sources Of increased erosion in the Clear Lake watershed include agricultural practices including recent conversion of agricultural land to vineyards, lakeside dredge and fill operations, and deposition of mine overburden.



[a] **[b]**

[c]

Figure 4-1. Regression plots of Suspended Solids vs. Total Phosphorus at (A) Kelsey Creek at Soda Bay Rd., (b) Middle Creek at Rancheria, and (c) Scotts Creek at Eikhoff Rd.

Evidence of anthropogenic sedimentation can be found in lakebed sediment cores. These cores suggest a significant increase in the rate of sedimentation beginning around 1927, when motorized earth-moving equipment began to be applied to industries such as gravel-mining, road-building, agriculture, and other industries in the Clear Lake watershed. With the exception of wetland reclamation projects, little of the post–1927 increase in sedimentation can be attributed to agricultural development or land use practices. Goldstein and Tolsdorf (1994) calculated that erosion from "miscellaneous lands" accounted for approximately 55% of the erosion occurring in the basin, which included cropland, public and private logging areas, off-highway vehicle (OHV) recreational areas, and low density development, making it impossible to isolate the agricultural component. A related study by Richerson et al. (1994) concluded that Middle Creek, Scotts Creek, and Kelsey Creek contribute from 1/2 to 1/3 of the total sediment and phosphorus load entering Clear Lake on an annual basis. Because these creeks drain the most extensive agricultural regions in the basin, it can be reasoned that some proportion of the sediment and nutrient load in these creeks is derived from accelerated erosion on cropland. However, the methods used in this study make it again not possible to isolate the absolute or even the relative contributions from cropland alone. With exception of an erosion and water quality report prepared by the County (Lake County 1999), documented evidence of accelerated erosion and sedimentation occurring on agricultural lands in the basin is generally lacking.

Beginning in the late 1980s, an agricultural conversion from walnut orchards to wine grape vineyards has been occurring in the Clear Lake watershed. These conversions result in an increase in the erosion hazard on a converted parcel due to accelerated sheet, rill, and gully erosion during and for several years after the process is complete. Although there are no quantitative data regarding this process, orchard-to vineyard conversion impacts on erosion and sedimentation rates are estimated to be short-term in nature. However, conversion of native vegetation to vineyards likely increases both short- and long-term erosion and sedimentation rates unless extensive erosion and sediment control measures are implemented. Regardless of their specific short- and long-term effects on erosion and sedimentation rates, the accelerated erosion that results from both types of vineyard conversion projects probably results in the loss of substantial quantities of topsoil to erosion.

Limited information exists regarding groundwater contribution of nutrients in the Clear Lake watershed. However, it can be reasonably expected that unconfined aquifers underlying agricultural and unsewered urban areas exhibit elevated nutrient concentrations relative to less-developed regions in the watershed. However, worst-case scenario studies conducted in 1983 (Reckhow and Chapra, 1983) estimate that a maximum of 4 percent of the total available phosphorus could originate from septic system leakage and be discharged to Clear Lake via stream discharge. More detailed relationships between landuse type and groundwater quality were not available based on limited data and the variability in concentrations, but based on low groundwater flow contributions, aquifers in the Clear Lake watershed are thought to be a negligible source of nutrients (Lake County/UCD Clean Lakes Project: Final Report, July 1994).

Historical loss of wetland areas due to agricultural expansion in the Clear Lake watershed has reduced its capacity to remove nutrients and the sediments to which they are sorbed. Estimates of wetland loss in the Clear Lake watershed are as high as 85% relative to 1840 acreage (Suchanek et al., 1994), with significant losses occurring in the Robinson and Tule Lake region of the watershed. The Tule Lake system, in the northern extent of the watershed, demonstrates an effective phosphorus removal mechanism. The original Robinson Lake wetlands, downstream of Tule Lake, are thought to have functioned as effectively prior to hydromodification due to reclamation and flood control projects.

In 1990, EPA developed rules establishing Phase I of the National Pollutant Discharge Elimination System (NPDES) storm water program, designed to prevent harmful pollutants from being washed by storm water runoff into Municipal Separate Storm Sewer Systems (MS4s) (or from being dumped directly into the MS4) and then discharged from the MS4 into local waterbodies. Phase I of the program required operators of medium and large MS4s (those generally serving populations of 100,000 or greater) to implement a storm water management program as a means to control polluted discharges from MS4s. Phase II of the rule extends coverage of the NPDES storm water program to certain small municipalities with a population of at least 10,000 and/or a population density of greater than 1,000 people per square mile. Small MS4s are defined as any MS4 that is not a medium or large MS4 covered by Phase I of the NPDES Storm Water Program. There are no large or medium MS4s in the Clear Lake watershed. However, Clearlake is a small MS4.

4.2 Model Selection Criteria

In order to represent nutrient sources, evaluate interrelationships among water quality constituents, and support objectives outlined by the RWQCB and EPA, development of a comprehensive linked watershed/receiving water modeling system is necessary to represent the Clear Lake system. A watershed model is essentially a series of algorithms applied to watershed characteristics and meteorological data to simulate land-based processes over an extended period, including hydrology and pollutant transport. Many watershed models are also capable of simulating in-stream processes using the land-based calculations as input.

Receiving water models are composed of a series of algorithms applied to characteristics data to simulate flow and water quality of the waterbody. The characteristics data, however, represent physical and chemical aspects of a lake, river, or estuary. These models vary from simple 1-dimensional box models to complex 3-dimensional models capable of simulating water movement, salinity, temperature, sediment transport, pollutant transport, and bio-chemical interactions occurring in the water column.

In selecting an appropriate modeling platform to support regulatory and managerial initiatives, the following criteria have been considered and addressed (expanding on classification of Mao, 1992):

- Technical Criteria
- Regulatory Criteria
- User Criteria

Technical criteria refer to the model's capability of simulating the physical system in question, including watershed and/or receiving water characteristics/processes and constituents of interest. Regulatory criteria make up the constraints imposed by regulations, such as water quality standards or procedural protocol. User criteria comprise the operational or economical constraints imposed by the end-user and include factors such as hardware/software compatibility and financial resources. The following discussion details considerations within each of these categories specific to the Clear Lake system.

4.2.1 Technical Criteria

The watershed and surface waters of Clear Lake present a challenging system for modeling hydrology and water quality. This section outlines key functions and processes that are necessary for consideration in the selection of an appropriate modeling strategy, and is divided into three main topics: Physical Domain, Source Contributions, and Constituents. Consideration of each topic was critical in selecting the most appropriate modeling system to address the types of sources and the numeric targets associated with the listed waters.

4.2.1.1 Physical Domain

Representation of the physical domain is perhaps the most important consideration in model selection. The physical domain is the focus of the modeling effort—typically, either the receiving water itself or a combination of the contributing watershed and the receiving water. Selection of the appropriate modeling domain depends on the constituents of interest and the conditions under which the receiving water exhibits impairment. For a receiving water dominated by point source inputs that exhibits impairments under only low-flow conditions, a steady-state approach is typically used. This type of modeling approach focuses on only in-stream (receiving water) processes during a user-specified condition. For receiving waters affected additionally or primarily by rainfall-driven flow and pollutant contributions, or by internal loading episodes such as those in the Clear Lake system, a dynamic approach is recommended.

Dynamic models consider time-variable nonpoint source contributions from a watershed surface or subsurface, or throughout the water column of a receiving water body. Some models consider monthly or seasonal variability, while others enable assessment of conditions immediately before, during, and after individual rainfall events. Dynamic models require a substantial amount of information regarding input parameters and data for calibration purposes.

4.2.1.2 Source Contributions

Primary sources of pollution to a waterbody must be considered in the model selection process. Accurately representing contributions from permitted point sources and nonpoint source contributions from urban, agricultural, and natural areas is critical in properly representing the system and ultimately evaluating potential load reduction scenarios.

Available information regarding nutrient loading in the Clear Lake system watershed indicate the main sources are from scour of native soils, unpaved roads, Hydromodification (gravel mining), agricultural land use, removal of riparian vegetation, and channel erosion (Lake County/UCD Clean Lakes Project: Final Report, July 1994). As a result the model(s) selected to develop nutrient TMDLs for the Clear Lake system must be able to address the major source categories considered controllable for TMDL implementation purposes.

4.2.1.3 Constituents

Another important consideration in model selection and application is choosing appropriate constituents to simulate. Choice of state variables is a critical part of model implementation. The more state variables included, the more difficult the model will be to implement and calibrate. However, if key state variables are omitted from the simulation, the model might not simulate all necessary aspects of the system and might produce unrealistic results. A delicate balance must be met between minimal constituent simulation and maximum applicability.

The focus of development of the TMDL for Clear Lake is to reduce the frequency and intensity of algal blooms that occur as the result of nutrient cycling. Nutrient cycling is extremely complex, and accurate estimation of nutrient loading relies on a host of interrelated factors. The transport of nutrients from point of origin into stream channels, from streams into the lake, and ultimately within the lake, is also influenced by multiple factors. The relative impact of external nutrient loading to the lake and internal loading must be represented by the modeling system, as these transport and storage mechanisms and their influence on the impairment must be addressed.

4.2.2 Regulatory Criteria

To assist the RWQCB and EPA in TMDL development activities, a properly designed and applied model must provide the source-response linkage component of the TMDL and enable accurate assimilative capacity assessment and allocation distribution. A waterbody's assimilative capacity is determined through adherence to predefined water quality criteria. The Water Quality Control Plan for the Sacramento and San Joaquin River Basins establishes, for all waters within the basin, including Clear Lake, the beneficial uses for each waterbody to be protected, the WQOs that protect those uses, and an implementation plan that accomplishes those objectives. The Basin Plan does not specify numeric water quality criteria for biostimulatory substances. However, to accommodate the beneficial uses for Clear Lake, a chlorophyll-a concentration target has been identified based on an intensive modeling study implementing the following applications.

4.2.3 User Criteria

User criteria are determined by the needs, expectations, and resources of the CVRWQCB and EPA. Modeling software must be compatible with existing UNIX- or personal-computer-based hardware platforms, and due to future use for planning and permitting decisions, should be well-documented, tested, and accepted. From a resource perspective, the level of effort required to develop, calibrate, and apply the model must be commensurate with available funding, without compromising the ability to meet technical criteria. In addition to these primary criteria, the required time-frame for model development, application, and completion is important.

4.3 Model Selection

Establishing the linkage between the in-stream water quality targets and source loading is a critical component of TMDL development. It allows for the evaluation of management options that achieves the desired source load reductions. The link can be established through a number of techniques, ranging from qualitative assumptions based on sound scientific principles to sophisticated modeling techniques. Ideally, the linkage is be supported by monitoring data that allow the TMDL developer to associate certain waterbody responses to flow and loading conditions. The objective of this section is to present the approach taken to develop the linkage between sources and in-stream responses for TMDL development in the Clear Lake system.

Modeling Clear Lake presents a challenge using currently available modeling tools. The system involves various unique hydraulic features including: steep upland watersheds with adjacent lowland plains, a large lake to watershed area ratio, storage of headwaters in reservoirs, sediment and nutrient settling in these reservoirs, internal and external loading of nutrients, and various management practices that potentially enhance or impede flow and nutrient loading. In addition, to assist in TMDL development and to provide decision support for watershed management, the model was used to simulate various scenarios to address specific management and environmental factors. Additional scenarios may be run based on augmentation of input data to be collected in ensuing monitoring efforts, future implementation of various management strategies or BMPs, or adaptation and linkage to additional models developed in subsequent projects. Therefore, model flexibility is a key attribute for model selection.

The modeling system selected is divided into two components representative of the processes essential for accurately modeling hydrology, hydrodynamics, and water quality in the Clear Lake system. The first component of the modeling system consists of a watershed model that predicts stormwater runoff and external pollutant loading as a result of rainfall events. The second component includes a hydrodynamic model to simulate the complex water circulation and pollutant transport patterns in Clear Lake and its tributaries.

The models selected for the Clear Lake TMDL are components of EPA's TMDL Modeling Toolbox (Toolbox; http://www.epa.gov/athens/wwqtsc/), which has been developed through a joint effort between EPA and Tetra Tech, Inc. The Toolbox is a collection of models, modeling tools, and databases that have been utilized over the past decade in the determination of TMDLs for impaired waters. A detailed description of each component of the modeling system follows.

4.3.1 Watershed Model: Loading Simulation Program C++ (LSPC)

USEPA's Loading Simulation Program in C++ (LSPC) was selected for simulation of watershed processes, including hydrology and pollutant accumulation and washoff. LSPC is a component of the EPA's TMDL Modeling Toolbox. It integrates a geographical information system (GIS), comprehensive data storage and management capabilities, a dynamic watershed model (a recoded version of EPA's Hydrological Simulation Program–FORTRAN [HSPF]), and a data analysis/post-processing system into a convenient PC-based windows interface that dictates no software requirements. The LSPC model is capable of predicting water quantity and quality from large, complex watersheds with variable land uses, elevations, and soils. Because it is physically based, rather than empirically, the model requires specific input data, such as weather, soils, land use, and topography. This offers the ability to apply the model in areas where observation data are sparse. The model can simulate nutrient contributions from specific source areas (e.g., subwatershed or land use areas). This is important in terms of TMDL development and allocation analysis. Details regarding the theoretical structure of the LSPC model and its modules can be found in the *Hydrologic Simulation Program FORTRAN User's Manual for Release 11* (USEPA, 1996) document.

LSPC is the ideal model to meet the selection criteria outlined in Section 4.1, with many advantages over other available watershed models. While LSPC and HSPF are similar models fundamentally, LSPC offers a number of advantages over HSPF and currently available platforms for running HSPF (such as NPSM in BASINS 2.0 or WinHSPF in BASINS 3.0). Advantages in using LSPC (and the Toolbox for linkage to a separate hydrodynamic model) include:

- LSPC provides storage of all geographic, modeling, and point source permit data in a Microsoft Access database and text file formats – thus data manipulation is efficient and straightforward.
- LSPC presents no inherent limitations regarding the size and number of watersheds and streams that can be modeled.
- LSPC can be easily linked to other models (advanced hydrodynamic and water quality models such as EFDC and WASP) in a modular fashion.
- LSPC can be easily modified to include additional features that are specific to the Clear Lake watershed - such features include flow diversions from irrigation and flood control.
- LSPC provides the user the ability to specify and develop queries to generate unique reports of model results.
- LSPC provides post-processing and analytical tools designed specifically to support TMDL development and reporting requirements (including a TMDL calculator).
- LSPC contains an archival mechanism for saving each and every model run (critical to support the administrative record for TMDL development and for model transfer between users).
- LSPC includes a customized GIS interface that does not require user-purchased software (critical for the public participation process/stakeholder input).

4.3.2 Environmental Fluid Dynamics Code (EFDC)

The Environmental Fluids Dynamic Code (EFDC) was utilized for the hydrodynamic and water quality modeling of Clear Lake. EFDC is a general purpose modeling package for simulating one- or multi-dimensional flow, transport, and bio-geochemical processes in surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions. The EFDC model was originally developed by Hamrick (1992) at the Virginia Institute of Marine Science for estuarine and coastal applications and is considered public domain software. This model is now EPA-supported as a component of the Toolbox, and has been used extensively to support TMDL development throughout the country. In addition to hydrodynamic, salinity, and temperature transport simulation capabilities, EFDC is capable of simulating cohesive and non-cohesive sediment transport, near field and far field discharge dilution from multiple sources, eutrophication processes, the transport and fate of toxic contaminants in the water and sediment phases, and the transport and fate of various life stages of finfish and shellfish. The EFDC model has been extensively tested, documented, and applied to environmental studies world-wide by universities, governmental agencies, and environmental consulting firms.

The structure of the EFDC model includes four major modules: (1) a hydrodynamic model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics model. The EFDC hydrodynamic model is composed of six transport modules including dynamics, dye, temperature, salinity, near field plume, and a tracer module which simulates the movement of neutrally buoyant drifters released in each three-dimensional model cell at specified time sequences. These capabilities encompass the requirements of the Clear Lake TMDL project.

5 TECHNICAL APPROACH

5.1 Watershed Model Configuration

The LSPC model was configured for the Clear Lake watershed and was used to simulate the watershed as a series of hydrologically connected subwatersheds. The specific constituents modeled by LSPC were flow, phosphorus, and nitrogen, which served as boundary condition data for the EFDC receiving water model. The watershed model was also used as a platform for representing scenarios for phosphorus load reductions. Development and application of the watershed model to address the project objectives involved two important steps:

1. Configuration of Key Model Components
2. Model Calibration and Validation

5.1.1 Configuration of Key Model Components

The following components provide the basis for the model's ability to estimate flow and nutrient sources. Hydrologic representation refers to the LSPC modules or algorithms used to simulate hydrologic processes (e.g., surface runoff, evapotranspiration, and infiltration).

Watershed Segmentation

Watershed segmentation refers to the subdivision of the Clear Lake watershed into smaller, discrete subwatersheds for modeling and analysis. This subdivision was primarily based on the stream networks and topographic variability, 7.5-minute United States Geologic Survey (USGS) topographic quadrangles, stream connectivity (from the National Hydrography Dataset [NHD]), locations of flow and water quality monitoring stations, and existing watershed delineations (from data provided by Lake County department of Public Works). To represent loadings and resulting concentrations of nutrients in the Clear Lake watershed, the watershed was divided into 49 subwatersheds (Figure 5-1).

Land Use Representation

The land use representation provides the basis for distributing soils and pollutant loading characteristics throughout the basin. The watershed model requires a basis for distributing hydrologic and pollutant loading parameters to appropriately represent hydrologic variability throughout the basin, which is influenced by land surface and subsurface characteristics. It is also necessary to represent variability in pollutant loading, which is highly correlated to land practices. The basis for this distribution was

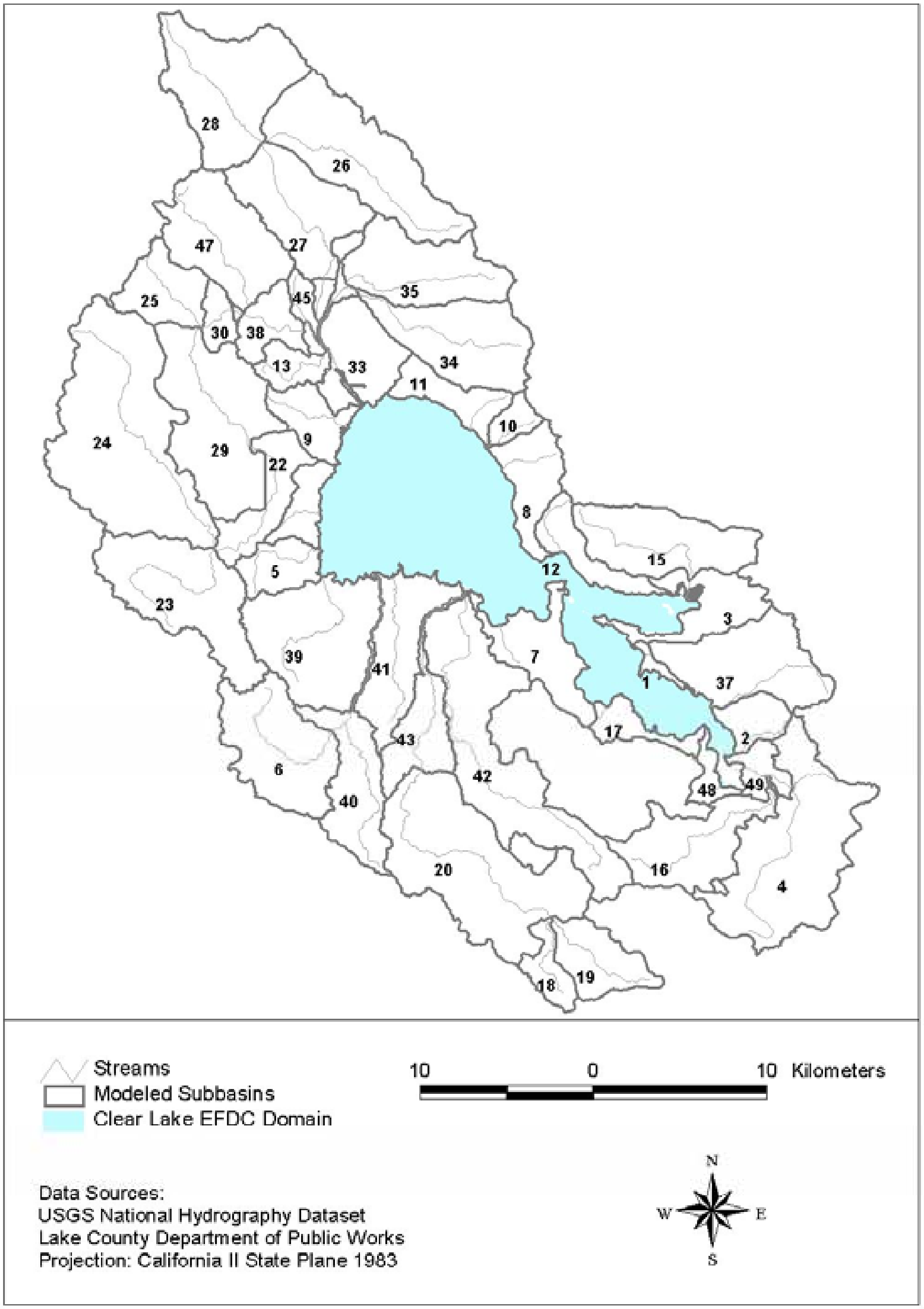


Figure 5-1. Modeled Subbasins in the Clear Lake Watershed.

provided by land use coverage of the entire watershed. Land use data used to configure the Clear Lake LSPC model were obtained from the Multi-Resolution Land Characterization (1992) database.

Although the multiple categories in the land use coverage provide much detail regarding spatial representation of land practices in the watershed, such resolution is unnecessary for watershed modeling if many of the categories share hydrologic or pollutant loading characteristics. Therefore, many land use categories were grouped into similar classifications, resulting in a subset of 8 categories for modeling. Table 5-1 shows the original MRLC land use categories for the watershed and the corresponding LSPC grouping. These land use data provide a foundation upon which the significance of nonpoint sources can be estimated.

LSPC algorithms require that land use categories be divided into separate pervious and impervious land units for modeling. This division was made for the appropriate land uses (primarily urban) to represent impervious and pervious areas separately. Sources for this division into pervious and impervious included: 1) estimates provided by local contacts who are familiar with the area, 2) estimates derived from assessments from the aerial photographs, and 3) estimates based on typical impervious percentages associated with different land use types from the Soil Conservation Service's TR-55 Manual. LSPC model algorithms that simulate hydrologic and pollutant loading processes for pervious and impervious lands was then applied to the corresponding land units.

Generally, paved roads are accounted for in the Clear Lake LSPC model through the urban pervious and urban impervious land use categories (high intensity commercial/ industrial/transportation designation in MRLC). This coverage does not provide an accurate representation of road densities, especially unpaved roads, for areas of the watershed where roads and unpaved roads are known to contribute significantly to sediment loading. To better represent the loading from these areas, additional road density information was obtained. A spatial data layer obtained from the LCDPW provided detailed data on dirt and paved road densities and distributions in the Clear Lake watershed. The distribution of roads was assessed on a subwatershed basis and representative modifications were made to the land use distribution at this scale.

Table 5-1. Land Use Code Conversion from MRLC to LSPC.

Original MRLC Category	LSPC Category	Percent Pervious
Open water	Water	100
Bare rock/sand/clay	Barren	100
Row crops	Cropland	100
Planted/cultivated (orchards, vineyards, groves)	Cropland	100
Small grains	Cropland	100
Deciduous forest	Forest	100
Evergreen forest	Forest	100
Mixed forest	Forest	100
Deciduous shrubland	Forest	100
Grassland/herbaceous	Forest	100

Pasture/hay	Pasture	100
Other grasses (urban/recreational; e.g. parks, lawns)	Pasture	100
Quarries/strip mines/gravel pits	Strip mining	100
Low intensity residential	Urban pervious	81
	Urban impervious	19
High intensity residential	Urban pervious	35
	Urban impervious	65
High intensity commercial/industrial/transportation	Urban pervious	20
	Urban impervious	80
Transitional	Urban pervious	90
	Urban impervious	10
Woody wetlands	Wetlands	100
Emergent herbaceous wetlands	Wetlands	100

Hydrology Representation

Hydrologic representation refers to the LSPC modules or algorithms used to simulate hydrologic processes (e.g., surface runoff, evapotranspiration, and infiltration). The LSPC PWATER (water budget simulation for pervious land segments) and IWATER (water budget simulation for impervious land segments) modules, which are identical to those in HSPF, were used to represent hydrology for all pervious and impervious land units (Bicknell et al., 1996). Designation of key hydrologic parameters in the PWATER and IWATER modules of LSPC were required. These parameters are associated with infiltration, groundwater flow, and overland flow. USDA's STATSGO Soils Database served as a starting point for designation of infiltration and groundwater flow parameters. For parameter values not easily derived from these sources, documentation on past HSPF applications were accessed, particularly the recent modeling studies performed. Starting values were refined through the hydrologic calibration process (described in the next section).

Soil detachment by rainfall on the contributing land uses is simulated in the LSPC model, which subsequently requires that the dominant soil type for each subwatershed be assigned by subwatershed. Soils data were obtained from STATSGO. Detached sediment is removed by surface flow and is washed off into the stream reach where it eventually settles and is available for resuspension into the water column.

Pollutant Representation

Based on analysis of the water quality data in the Clear Lake watershed as well as review of previous studies, possible nonpoint sources of nutrients include agriculture, urban/residential areas, streambank erosion, sand and gravel mining, and rangeland. There are currently no traditional permitted point sources of sediment or nutrients in the Clear Lake watershed.

The primary pollutants represented in the watershed model to estimate loadings to Clear Lake included sediment, nitrogen, and phosphorus. Loading processes for pollutants were represented for each land unit using the LSPC PQUAL (simulation of quality constituents for pervious land segments) and IQUAL (simulation of quality constituents for impervious land segments) modules, which are identical to those in HSPF. These modules simulate the association of pollutants with sediment, which is simulated as being scoured from pervious land segments and washed-off during storm events. Initial parameter values used to estimate washoff coefficients and exponents for sediment scour from the watershed were initially estimated based on in-stream rating curves. These starting values served as baseline conditions for sediment and water quality calibration; the appropriateness of these values to the Clear Lake watershed was validated through comparison to local water quality data during the calibration process (described in the next section). Although atmospheric deposition may be an issue in the watersheds, it was not explicitly simulated in the watershed model. It was, however, represented implicitly in the model through use of the land use- and pollutant-specific sediment potency rates.

Meteorological Representation

Meteorological data are a critical component of the watershed model, and appropriate representation of precipitation, wind speed, potential evapotranspiration, cloud cover, temperature, and dew point are required to develop a valid modeling system. These data provide necessary input to LSPC algorithms for hydrologic and water quality representation. Meteorological data have been accessed from a number of sources in an effort to develop the most representative dataset for the Clear Lake watershed. These sources are shown in Table 5-2.

LSPC requires appropriate representation of precipitation and potential evapotranspiration. Temperature data was used to calculate hourly potential evapotranspiration values necessary for input to LSPC. In general, hourly precipitation data are recommended for hydrologic modeling to assist in assessment of pollutant loading (although in some cases, such as small, flashy, highly urbanized watersheds 15-minute data may be necessary). Therefore, only weather stations with hourly-recorded data have been considered thus far in the precipitation data selection process. Rainfall-runoff processes for each subwatershed were driven by precipitation data from the most representative station. Meteorological data from five stations near Clear Lake were assessed for the watershed model.

Table 5-2. Meteorological Stations Used in the Modeling Process

Station	Data Source	Year Range	Hourly Precipitation	Minimum/ Maximum Temperature	Hourly Temperature	Solar Radiation
Kelseyville	CPC	1998-2002	yes	yes	yes	yes
Upper Lake	CPC	1998-2002	yes	yes	yes	no
Mt. Konocti	CPC	1998-1999	yes	no	yes	no
Lyons Valley	BLM	1988-2002	yes	no	yes	no
Whispering Pines	DWR	1984-1996	yes	no	no	no

Notes: CPC = Climate Prediction Center
BLM = Bureau of Land Management
DWR = California Department of Water Resources.

These appropriate meteorological datasets were obtained from the California Data Exchange Center (CDEC), and from the University of California's Statewide Integrated Pest Management Program (UCIPM). These entities maintain online databases that were queried to obtain precipitation and air temperature data for use as input to the LSPC watershed model. The data obtained as a result of the queries was subjected to a QA/QC regime that identified gaps in data and unreasonable values that may misrepresent observed conditions. The cleaned data were subsequently formatted for use in the modeling effort.

Waterbody Representation

Waterbody representation refers to LSPC modules or algorithms used to simulate flow and pollutant transport through streams and rivers. Each delineated subwatershed was represented with a single stream assumed to be completely mixed, one-dimensional segments with a trapezoidal cross-section. The National Hydrography Dataset (NHD) stream reach network for USGS hydrologic units were used to determine the representative stream reach for each subwatershed. Once the representative reach was identified, slopes were calculated based on DEM data and stream lengths measured from the original NHD stream coverage. In addition to stream slope and length, mean depths and channel widths are required to route flow and pollutants through the hydrologically connected subwatersheds. Mean stream depth and channel width were estimated using regression curves that relate upstream drainage area to stream dimensions, and estimated Manning’s roughness coefficients were applied to each representative stream reach.

In addition to the streams which route flow and transport pollutants through the modeled stream network, reservoirs exist in the Clear Lake watershed that are large enough to impound a significant quantity of flow and pollutants (Tule Lake). To represent these reservoirs in the watershed model, the length, width, maximum depth, infiltration rate, and spillway height and width were obtained for each reservoir. The reservoirs impounded all upstream flow until the water depth exceeded the spillway height, causing overflow and thus contributing to downstream flow and reduced pollutant loading.

Modeling the Clear Lake watershed required routing flow and pollutants through numerous stream networks. These stream networks connect all of the subwatersheds represented in the watershed model. Routing required development of rating curves for major streams in the networks, in order for the model to simulate hydraulic processes. The rating curves consist of a representative depth-outflow-volume-surface area relationship. Hydraulic formulations typically estimate in-stream flow, water depth, and velocity using continuity and momentum equations. In-stream flow calculations were made using the HYDR (hydraulic behavior simulation) module in LSPC, which is identical to the HYDR module in HSPF. In-stream pollutant transport was performed using the ADCALC (advective calculations for constituents) and GQUAL (generalized quality constituent simulation) modules.

For stream segments of the Clear Lake watershed impacted by the hydraulics of Clear Lake itself, a separate hydrodynamic receiving water model was implemented. A complete description of this receiving water model is provided in Section 6.2.

5.1.2 *Model Calibration and Validation*

After initially configuring the Clear Lake watershed model, model calibration and validation was performed. This is generally a two-phase process, with hydrology calibration and validation completed before repeating the process for water quality since water quality modeling is dependent on an accurate hydrology simulation. Calibration refers to the adjustment or fine-tuning of modeling parameters to reproduce observations. Output from the watershed model was produced in the form of daily average flow for each of the subwatersheds, to match the DWR reporting interval. After comparing the results, key hydrologic parameters were adjusted and additional model simulations were performed.

Calibration of the hydrologic model was accomplished by adjusting model parameters until the simulated and observed water budgets matched. Then the intensity and arrival time of storm peaks was calibrated. For this part of the calibration, the parameters influencing flow peak characteristics were adjusted until the comparison can no longer be improved without degrading the water budget comparison. This iterative process was repeated until the simulated results closely represented the system and reproduced observed flow patterns and magnitudes. Calibration of the watershed model was performed at four locations in the watershed, to ensure that heterogeneities within the watershed are accurately represented. These locations are shown in Figure 5-2.

Three locations are monitoring stations measuring both streamflow and water quality, which include Scotts Creek at Eikhoff Road (SEK), Middle Creek at Rancheria (MRR), and Kelsey Creek at Soda Bay Road (KSB). These locations were used to calibrate the

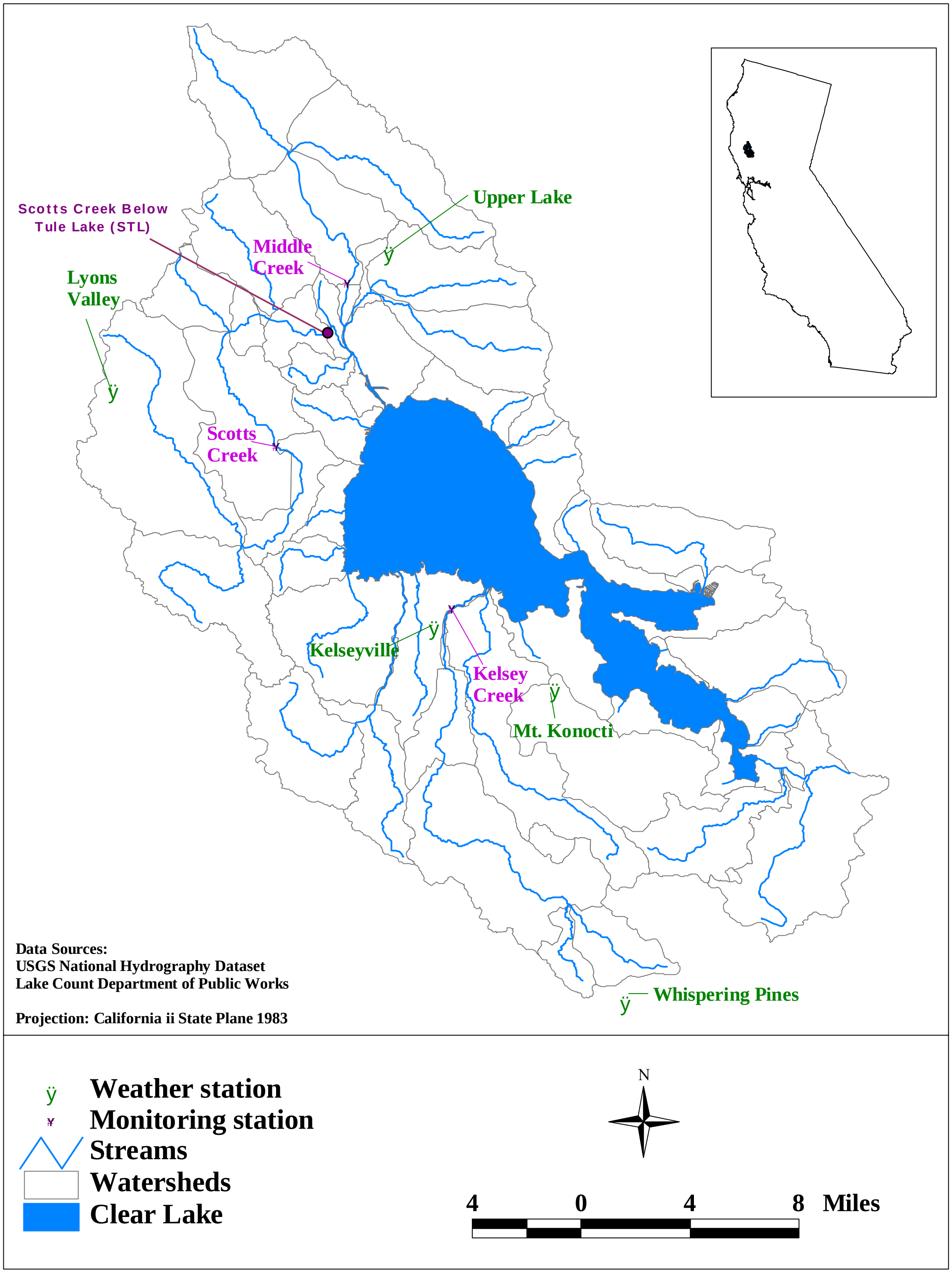


Figure 5-2. Location of monitoring stations used for calibration of the watershed model.

simulated hydrology to DWR stream gages considering the overall water budget, as well as storm peak and recession characteristics of the hydrograph at each location. These three stations were also used to calibrate a number of pollutants including sediment, total phosphorus, and total nitrogen. Two criteria for goodness of fit were used for calibration: graphical comparison and the relative error method. Graphical comparisons are extremely useful for judging the results of model calibration; time-variable plots of observed versus modeled flow provided insight into the model's representation of storm hydrographs, baseflow recession, time distributions, and other pertinent factors often overlooked by statistical comparisons. The model's accuracy was primarily assessed through interpretation of the time-variable plots. The relative error method was used to support the goodness of fit evaluation through a quantitative comparison. A small relative error indicates a better goodness of fit for calibration.

The calibration year(s) was selected based primarily upon the availability of observation data, and an examination of climate conditions to ensure that a range of hydrologic conditions (i.e low, mean, and high flow) were experienced during that period. Calibration for these conditions is necessary to ensure that the model will accurately predict a range of conditions for a longer period of time. Water year 1993 (September 1992- August 1993) was selected for calibration based on these factors and that two separate types of water quality data sets exist for that time period and provide increased assurance in the water quality component of the model. The results of the hydrology calibration are shown in Appendix B.

Key considerations in the hydrology calibration include the overall water balance, the high-flow-low-flow distribution, storm flows, and seasonal variation. Both graphical comparison and the relative error method were used to gage the calibration. Graphical comparisons were used to judge the results of model calibration; time-variable plots of observed versus modeled flow provide insight into the model's representation of storm hydrographs, baseflow recession, time distributions, and other pertinent factors often overlooked by statistical comparisons. The model's accuracy was primarily assessed through interpretation of the time-variable plots. The relative error method was used to support the goodness of fit evaluation through a quantitative comparison, but is not presented in this report. A small relative error indicates a better goodness of fit for calibration.

After calibrating watershed hydrology at the calibration locations, a validation of these hydrologic parameters was made through a comparison of model output to different time periods at the same gages (Table 5-3). The validation essentially confirmed the applicability of the regional hydrologic parameters derived during the calibration process, and were assessed in a similar manner to calibration: graphical comparison and the relative error method. The validation period of September 1993 through August 1995 was selected based on the availability of flow data at all three gages and a combination of average to wet years based on annual rainfall data. The results of the hydrology validation are shown in Appendix A.

Table 5-3. Flow Stations used for Hydrology Calibration and Validation

Station Number	Station Name	Historical Record	Selected Calibration Period	Selected Validation Period	Model Subwatershed
1	Scotts Creek	1981-1996	10/1/1992-9/30/1993	10/1/1993-9/30/1995	22
2	Kelsey Creek	1981-1996	10/1/1992-9/30/1993	10/1/1993-9/30/1995	43
3	Middle Creek	1981-1996	10/1/1992-9/30/1993	10/1/1993-9/30/1995	27

Overall, during model calibration the model predicted storm volumes and storm peaks well. Since the runoff and resulting streamflow is highly dependent on rainfall, occasional storms were over-predicted or under-predicted depending on the spatial variability of the meteorological and gage stations. The validation results also showed a good fit between modeled and observed values, thus confirming the applicability of the calibrated hydrologic parameters to the Clear Lake watershed.

After the model was calibrated and validated for hydrology, water quality simulations were performed. Water quality data recorded during all seasons at Scotts Creek (SEK), Kelsey Creek (KSB), and Middle Creek (MRR) were used to calibrate the water quality component of the LSPC model (Figure 5-2). The objective of the validation process was to best represent pollutant concentrations during storm events at monitoring stations throughout the region. The spatial variability of the three water quality calibration locations was excellent (i.e urban to open land uses, a range of physical characteristics); however, the temporal variability and total number of samples limited statistical analysis to basinwide summary statistics rather than comprehensive time series and relative error analyses at each monitoring location. The data used in the water quality calibration is summarized in Table 5-4.

Table 5-4. Basin wide Water Quality Data Used for Calibration and Validation.

Sample Location	Parameter	Period of Record	Number of Samples	Values (mg/L unless noted) Minimum	Mean	Maximum
Middle Creek Rancheria (MRR)	Temperature[a]	1992-2000	34	7.2	13.05	92
	pH[b]	1992-1994, 1999-2000	12	5.98	6.08	7.9
	Conductivity[c]	1992-2000	35	61	107.2	243
	Total suspended solids	1992-2000	48	93.68	512.74	1,704.93
	Total dissolved solids	1994-2000	46	45.9	97.45	184.33
	Total settable solids	1994-2000				
	Orthophosphate	1992-2000	56	0.03	0.15	0.54
	Total phosphorus	1992-2000	46	0.05	0.51	2.4
	Iron	1992	9	0.03	1.07	2.45
	Nitrogen	1992	5	0.7	0.56	1.2
Sample Location	**Parameter**	**Period of Record**	**Number of Samples**	**Values (mg/L unless noted)**		
				Minimum	**Mean**	**Maximum**
Kelsey Creek at Soda Bay Road (KSB)	Temperature[a]	1995-2000	23	8.1	11.28	15.6
	pH[b]	1999-2000	4	6.6	7.28	8.3
	Conductivity[c]	1995-2000	25	97.9	132.42	230
	Total suspended solids	1994-2000	36	116.81	381.46	1,102.84
	Total dissolved solids	1994-2000	36	70.97	115.64	174.17
	Total settable solids	1994-2000				
	Orthophosphate	1994-1998	36	0.06	0.16	0.42
	Total phosphorus	1994-1998	34	0.05	0.38	1.02
Scotts Creek at Eikhoff Road (SEK)	Temperature[a]	1992-1999	323	7	10.56	15.9
	pH[b]	993-1994, 1999-200	9	6.04	5.6	8
	Conductivity[c]	1992-2000	32	66.2	112.85	247
	Total suspended solids	1993-2000	39	100.84	344.77	987.94
	Total dissolved solids	1993-2000	37	25.75	102.01	148.8
	Total settable solids	1993-2000				
	Orthophosphate	1992-2000	40	0.05	0.12	0.36
	Total phosphorus	1993-1999	39	0.08	0.36	1.02
	Iron	1993-1994	8	0.03	0.28	0.9
	Nitrogen	1994	5	1	1.1	1.2

Note:

[a] Values are in degrees Celsius.

[b] Values are in standard units.

[c] Values are in μmhos/cm.

5.2 Receiving Water Model Configuration

Configuration of the EFDC receiving water model involved processing bathymetric data, developing a model grid, assigning initial hydrodynamic and water quality conditions in the water column, defining boundary conditions at the water surface, and linkage to the watershed model for up-stream and lateral inputs. The following discussion provides more detail regarding model configuration and application.

5.2.1 Grid Generation

The first step to configure EFDC for Clear Lake was to discretize the waterbody into a computational grid, in order to solve the model's governing equations. A boundary-fit curvilinear grid was developed to most truly represent the shape of the lake. Significant hydraulic features (including watershed inflows, dams, and major bathymetric variability) and their locations were considered in preparing the grid. The grid consists of 125 curvilinear grid cells. Each cell is represented by seven vertical layers. Figure 5-3 presents the computational grid of Clear Lake model. Grid cells near the inflow tributaries are represented at a higher resolution than those within the lake itself. It should be noted that this grid was developed and refined through an iterative process wherein model resolution, accuracy, and simulation time were optimized.

5.2.2 Water Quality Model Structure

In order to most accurately represent the complex chemical and biological interactions exhibited by Clear Lake, and blue-green algae blooms in particular, a detailed water quality framework was instituted. The EFDC model was configured to represent the limiting effects of different nutrients, the interactions between blue-green algae and other algal species, and nutrient fate and transport within the water column and between the water column and sediment. Three different algal groups and multiple forms of nitrogen, phosphorus, and carbon were simulated, as well as their combined impact on dissolved oxygen levels. The water column state variables simulated in the water quality model are:

i. Blue-green algae biomass
ii. Diatom biomass
iii. Green algae biomass
iv. Dissolved organic carbon
v. Labile particulate organic carbon
vi. Refractory particulate organic carbon
vii. Dissolved organic phosphorus
viii. Labile particulate organic phosphorus
ix. Refractory particulate organic phosphorus
x. Ortho-phosphate
xi. Dissolved organic nitrogen
xii. Labile particulate organic nitrogen
xiii. Refractory particulate organic nitrogen
xiv. Ammonia
xv. Nitrite/nitrate
xvi. Dissolved oxygen

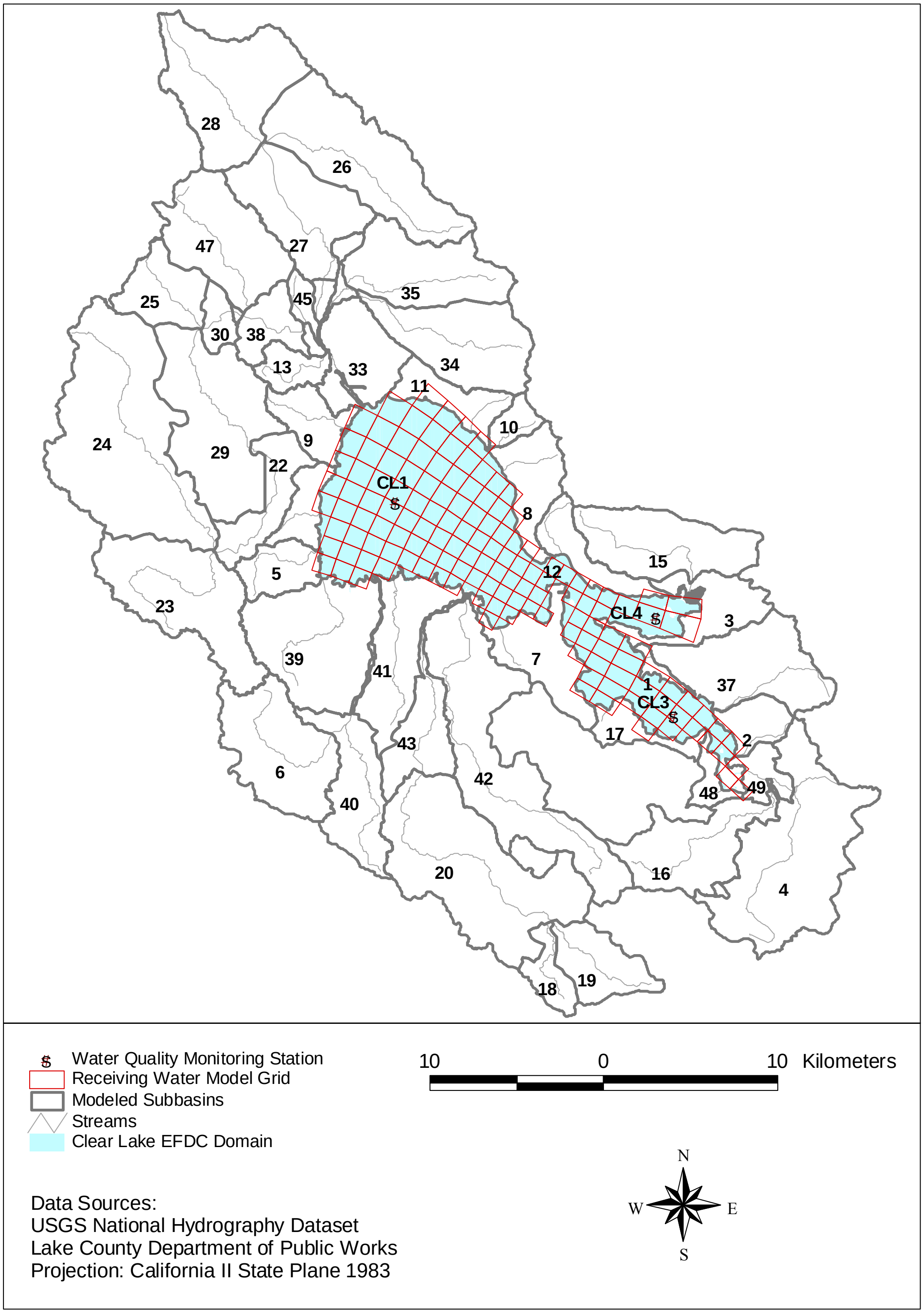


Figure 5-3. Computational Grid of the Clear Lake EFDC receiving water model.

In addition to representation of chemical and biological interactions within the water column, a sediment diagenesis model was also configured and linked to the water column model. The sediment diagenesis model enables the prediction of linked sediment nutrient flux, oxygen demand, and internal loading of nutrients for not only historical conditions, but also for nutrient management scenarios. This predictive capability overcomes the inherent limitation in many water quality models of statically setting sediment nutrient impacts. This capability is particularly useful during TMDL analysis, where loading scenarios should (and in reality, would) have a direct impact on sediment nutrient contributions to the water column.

To enhance the existing EFDC modeling framework, the following modules were developed and incorporated into the source code to specifically allow for more precise representation of eutrophication dynamics and TMDL development for Clear Lake:

a) *Nitrogen fixing function for blue-green algae*
   Nitrogen fixing plays an important role in the Clear Lake algae blooms since it not only provides an important nitrogen source to the lake for algae growth, but also serves to eliminate nitrogen limitation for blue-green algae. Therefore, the EFDC model was modified to simulate the ability of blue-green algae to fix nitrogen from the atmosphere.

b) *Luxury phosphorus consumption*
   Luxury phosphorus consumption refers to the phenomenon of algae uptaking more phosphorus from the water column in the presence of high water column phosphorus concentrations (and uptaking less in the presence of limited levels) (Cerco, 1994). This mechanism is very important for simulating the phosphorus-algae interaction in a highly eutrophic water body such as Clear Lake. The Clear Lake model simulates nutrient uptake by blue-green algae, green algae, and diatom populations to address the seasonal variation in phosphorus sinks. Without this mechanism, the model likely would not be able to predict the rise and drop in phosphorus concentrations associated with the variability in algae biomass.

5.2.3 Boundary Conditions

Model boundary conditions are fixed conditions applied to the modeling system. Flow gages, meteorological station data, and water quality data to for the Clear Lake EFDC model consist of both upstream/lateral boundary conditions and surface boundary conditions. The upstream/lateral boundary conditions include the inflow water and associated sediment, temperature and water quality constituents. The surface boundary condition is represented by time variable meteorological conditions including solar radiation, wind speed and direction, air temperature, atmospheric pressure, relative humidity, and cloud cover conditions.

In the Clear Lake model, upstream/lateral boundary conditions were configured based on the watershed modeling results. The spatial representation of the upstream/lateral boundary conditions was determined by mapping the geographical coordinates of the tributary outlets to the lake model grid. Flow, temperature, sediment, and pollutant loading time series data from the watershed model for each tributary watershed and intervening watershed (those not draining major streams to the lake) were applied to corresponding grid cells within the lake model. A program was developed to extract the watershed modeling results and convert them into an EFDC-compatible format. This helped form a seamless linkage between the watershed and lake models. Although a flow gage is located 4 miles downstream of Clear Lake on Cache Creek, a control structure was incorporated into the model at the outlet grid cell. The control structure was used to address the damping effect caused by the distance between the lake and the gage, as instantaneous gage flows applied to the model were found to cause unrealistic water surface elevation results in the model domain. This control structure represented outflow from the lake based on the lake water surface elevation. A nonlinear weir equation was incorporated into the EFDC model to approximate the relationship between the lake stage and the discharge flow, and the coefficients of the equation were calibrated using the observed lake elevation. In total, the model has 20 upstream/lateral inflow boundary conditions and one outflow boundary condition at the downstream.

The EFDC model requires atmospheric boundary forcing data which includes atmospheric pressure, air temperature, relative humidity, precipitation, evaporation, solar radiation, cloud cover, wind speed, and wind direction to drive the hydrodynamic simulation. Due to the physical characteristics of the lake, namely its large surface area, atmospheric forcing functions have a significant impact on water circulation patterns. Therefore, data from all stations in close proximity to Clear Lake were evaluated for application to the model. Stations were evaluated based on their proximity to the lake, period of record, parameters measured, and completeness of data. Although a number of stations exist in the vicinity of Clear Lake, most of the stations either have not measured all required parameters or are located too far from the lake (or are separated from the lake by a mountain ridge). Table 5-5 and Figure 5-4 show the characteristics and locations of each station considered.

Table 5-5. Meteorological Stations in the vicinity of Clear Lake.

Name	Agency	Station ID	Time period	Elevation (ft)	Relevant Parameters	Latitude	Longitude
Soda Creek	USFS	SOD	1/1/95/ on-going	1773	Temperature, precipitation, wind speed & direction, relative humidity	39.4330	-122.9830
High Glade	USFS	HYG	6/3/99/ on-going	4840	Temperature, precipitation, wind speed & direction, solar radiation, relative humidity	39.2040	-122.8050
Whispering Pines	DWR	WSP	1/1/96/ on-going	2700	Only precipitation	38.8000	-122.7170
Clear Lake Highlands	NWS	Clearlake 4S	1/1/89 / on-going	1340	Only precipitation	38.9000	-122.6000
Knoxville Creek	USBLM	KNO	1/1/95/ on-going	2200	Temperature, precipitation, wind speed & direction, solar radiation, relative humidity	38.8830	-122.4170
Clearlake C	UCIPM	NCDC1806	2/20/1958 / on-going	1349	Temperature, precipitation	38.9000	-122.6000
Lakeport C	UCIPM	NCDC4701	1/1/51 to 7/31/01	1315	Temperature, precipitation	39.0330	-122.9170
Lakeport T	UCIPM	NCDC34	3/4/96 to 8/22/01	1330	Temperature, precipitation, Wind speed/ direction	39.0830	-122.9170
Kelseyville-01.P	UCIPM	KEL	3/18/98 / on-going	1352	Temperature, precipitation, wind speed & direction, solar radiation, relative humidity	39.0000	-122.8500
Middletown-01.P	UCIPM	MID	3/13/98 / on-going	1201	Temperature, precipitation, wind speed & direction, relative humidity	38.7000	-122.6170
Mt. Konocti-01.P	UCIPM	KON	3/20/98 to 8/26/99	4298	Temperature, precipitation, wind direction	38.9670	-122.7670
Red Hills-02.P	UCIPM	RED	3/20/02 / on-going	2002	Temperature, precipitation, wind speed & direction, solar radiation, relative humidity	38.9170	-122.7330
Scotts Valley-02.P	UCIPM	SVL	1/17/03 / on-going	1421	Temperature, wind direction, relative humidity	39.0670	-122.9500
Upper Lake-01.P	UCIPM	UPL	3/16/98 / on-going	1381	Temperature, precipitation, wind speed & direction, relative humidity	39.2000	-122.8830
Lyons Valley	USBLM	LYO	1/1/95 to on-going	3200	Temperature, precipitation, wind speed & direction, relative humidity	39.1250	-123.0710

Note: USFS: US Forest Service; NWS: National Weather Service; DWR: CA Dept of Water Resources; USBLM : US Bureau of Land Management; UCIPM: University of California Integrated Pest Management Program.

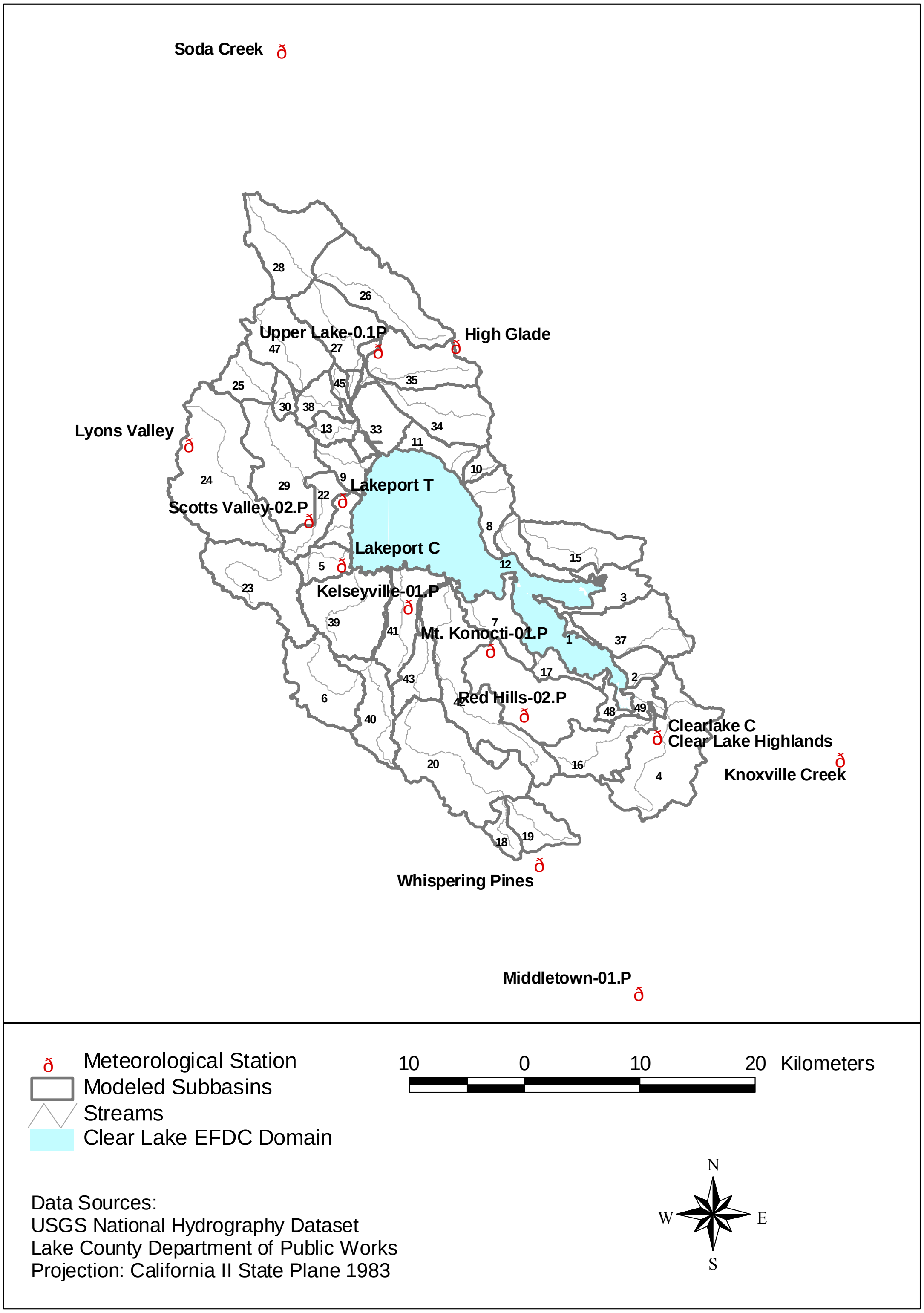


Figure 5-4. Meteorological Stations in the vicinity of Clear Lake.

Based on the evaluation, the Kelseyville-01.P station was used as the basis for creating the meteorological file. This station has measured all required parameters, provides the most complete data record for model application, and is located in close proximity to the lake. Due to topography and elevation for this station, it is also assumed to most closely represents wind speeds and the ambient air conditions for the lake (both of which are critical in the modeling effort). Because even the Kelseyville-01.P station did not have a complete record, a synthetic dataset was generated by recycling data prior to 1998 to fill in data gaps up to 1995 (which was used for model testing).

It should be noted that none of the stations, including Kelseyville-01.P, measured atmospheric pressure and cloud cover. Regional stations provide incomplete datasets regarding these parameters, reducing the possibility for analysis of seasonal or long-term trends. Therefore, the atmospheric pressure was estimated based on the station's elevation, and cloud cover was estimated using precipitation data (assumed to be overcast or 0.95 during measurable precipitation and 0.05 during dry conditions). Precipitation data, although also lacking in completeness from some stations, was relatively complete compared to atmospheric pressure and cloud cover, which allowed the relationship to be applied to longer periods of observation. The gaps in solar radiation data were filled by calculating the clear sky solar radiation using latitude and longitude, and then adjusting the values based on the estimated cloud cover.

5.2.4 Initial Conditions

For the dynamic lake model, initial conditions provide a starting point for the model to march forward through time. A uniform temperature of 5^{o}C was specified as the initial condition everywhere in the water column. The initial water circulation velocity was specified as 0.0 for all dimensions. It should be noted that for simulation over a long time period, such as over a year or multiple years (as was the case for this simulation), the overall model performance is not sensitive to the initial conditions for velocity and temperature.

Initial water quality conditions, however, may have a significant impact on model predictions. Several numerical experiments with the Clear Lake model demonstrated that the timing and magnitude of summer algae blooms, as well as hypolimnetic anoxia development, are sensitive to the initial nutrient concentrations in the water column and organic matter concentrations in the sediment. Ideally, observed data should be used to specify these sensitive initial conditions. Insufficient water column and sediment data, however, were available to support specification of initial conditions. Therefore, a long-term simulation approach was used to derive the initial water quality conditions for the water quality model. This approach entailed extending the simulation period for multiple years prior to the calibration/validation period (described below) and running the model through the calibration/validation period. The initial conditions were thus determined through an iterative process that involved adjusting the initial conditions until model results during the calibration/validation period were within an acceptable range.

5.2.5 Model Calibration and Validation

Calibration of the EFDC hydrodynamic model was performed through a comparison of model predictions with various observed data, including lake stage and observed temperature profiles. Lake stage calibration was performed using the USGS Clear Lake at Lakeport (CKL) gage and data was obtained from CDEC. Temperature data from stations CL1, CL3, and CL4 were also used to support the hydrodynamic calibration and allow for a validation effort, since daily stage data was available from this station beginning on 1/1/1997. The location of the calibration stations are shown in Figure 5-5.

The EFDC model was calibrated to stage and temperature observations from 1/1/1997 to 12/31/1997. The hydrodynamic calibration was implemented in two steps. First, the lake stage was calibrated by adjusting the coefficients in the outflow weir equation until the simulated lake surface elevation agreed with the observed data reasonably well. Then, the model was calibrated to observed temperature profiles at stations CL1, CL3, and CL4. The major parameters adjusted at this point were the bottom friction coefficients. For both cases, model calibration was performed through a graphical comparison of model output and observed data to obtain a goodness-of-fit. This was deemed the most appropriate calibration comparison methodology due to limitations in meteorological data used to drive the model (since recycled data were used to drive the model and thus were not entirely reflective of variable local conditions). Hydrodynamic calibration results are presented in Appendix B. The hydrodynamic model was then validated using a similar approach for 1995 and 1996. The calibration and validation results for the hydrodynamic model indicate that the model performs reasonably well in simulating the water circulation and stratification patterns in Clear Lake.

Three calendar years (1995, 1996, and 1997) were selected as the years for water quality model calibration and validation, based on data availability. These three years represent a range of hydrologic conditions, including wet, normal, and relatively dry conditions.

In order to calibrate the model for 1995 and beyond, the model was run beginning in 1985. This provided a 10-year model initiation period which ensured that conditions in the water column and sediment were appropriate at the start of the actual calibration period. The lake model was run using LSPC-simulated flow and water quality loading, and the recycled meteorological data from 1998 to 2002 (since it was not specifically available for 1995). The simulated water quality concentrations in 1995 were then compared with the observed data (for dissolved oxygen and multiple forms of phosphorus and nitrogen). Values of major kinetic parameters and initial sediment organic matter concentrations were adjusted until a reasonable agreement between model results and observed data were achieved. As with the hydrodynamic calibration, calibration was evaluated through visual observation of time-variable results. The simulated dissolved oxygen, ammonia, and orthophosphate concentrations are very sensitive to the simulated algae population structures and biomass. Of the hundreds of calibration runs conducted, only a few runs resulted in acceptable balances of all parameters (chemical and biological) with respect to monitoring data.

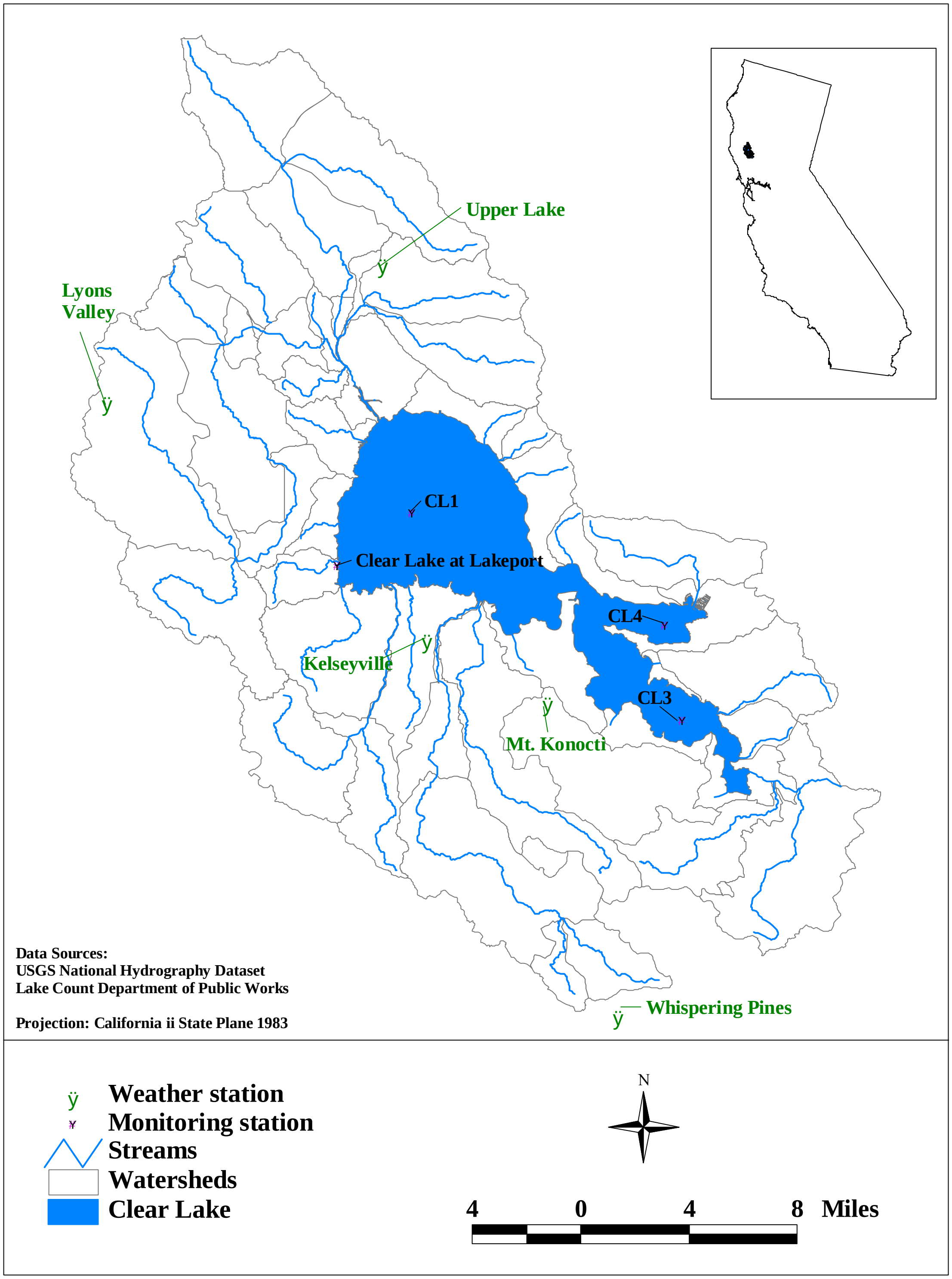


Figure 5-5. Location of monitoring stations used for calibration of the receiving water model.

After the model was calibrated for 1995, it was validated for 1996 and 1997 (under significantly different hydrologic conditions). Using 1996 and 1997 also allowed the model to be run as an extension of the calibration conditions (i.e., without resetting initial conditions for water column and sediment parameters). Water quality calibration and validation results are presented in Appendix D.

It should be noted that the model was not directly calibrated and validated for observed algae data, because algae observations were in the form of cell counts. Model results, on the other hand, were estimated in terms of biomass as carbon. Due to the large variability in cell size and dry mass content of different algae species, as well as the variability of the size and mass content of different individuals of the same algae species (Sun, 2003), it was not anticipated that a meaningful correlation could be achieved between cell count and biomass. More detailed information regarding dimensions of each cell and the bio-volume of each cell would be necessary. It can be assumed, however, that if algae biomass and population structure are not reasonably represented in the model, then the model would fail to accurately simulate the observed trend in dissolved oxygen and individual nutrient levels. Since the model represents the biological and chemical interactions in great detail, represents the sensitivity of algae to chemical concentrations (and vice versa), and accurately predicts dissolved oxygen and nutrient levels based on known forcing factors (incoming flows, nutrient loads, meteorology, etc.), it is assumed that algae dynamics are being simulated appropriately.

The EFDC model additionally provided a secondary validation of the performance of LSPC model in predicting upstream flow and nutrient loads. Without accurate prediction of upstream flow, successful calibration of the hydrodynamic and water quality model for Clear Lake would not have been possible. A great deal of effort was required to accurately predict hydrodynamic and water quality conditions within both frameworks (at the stream level and within the lake itself).

6 CRITICAL CONDITIONS AND SEASONAL VARIATION

The goal of the TMDL is to determine the assimilative capacity of a waterbody and to identify potential allocation scenarios that enable the waterbody to achieve WQOs under all conditions. The critical condition is the set of environmental conditions for which controls designed to protect water quality will ensure attainment of objectives for all other conditions. This is typically the period of time in which the stream exhibits the most vulnerability.

In the Clear Lake system, this period coincides with the summer season, particularly after multiple consecutive years of below average rainfall. The Data Analysis section discusses that higher phosphorus and nitrogen concentrations and low bottom DO concentrations tend to occur during the summer, coincident with higher blue-green algal productivity. Increased levels of phosphorus during summer periods directly affect blue-green algal productivity, while elevated nitrogen and decreased oxygen levels are associated but not the cause of increased productivity.

7 TMDL CALCULATION AND ALLOCATIONS

A TMDL for a given pollutant and waterbody is comprised of the sum of individual wasteload allocations (WLAs) for point sources, and load allocations (LAs) for both nonpoint sources and natural background levels. In addition, the TMDL must include a margin of safety (MOS), either implicitly or explicitly, to account for the uncertainty in the relationship between pollutant loads and the quality of the receiving waterbody. Conceptually, this definition is represented by the equation:

$$\text{TMDL} = \sum \text{WLAs} + \sum \text{LAs} + \text{MOS}$$

The TMDL is the total amount of pollutant that can be assimilated by the receiving waterbody while still achieving WQOs. In TMDL development, allowable loadings from pollutant sources that cumulatively amount to no more than the TMDL must be established; this provides the basis to establish water quality-based controls. TMDLs can be expressed on a mass loading basis (e.g., pounds of phosphorus per year) or as a concentration in accordance with 40 CFR 130.2(l).

7.1 Wasteload Allocations

Federal regulations (40 CFR 130.7) require TMDLs to include individual WLAs for each point source. As part of Phase II of the NPDES stormwater permitting program, the operator of Clearlake is required to adopt stormwater management programs to control entry of pollutants to local waterways. Any loads associated with these MS4s must be incorporated into the TMDL as part of the Waste Load Allocation.

MS4 phosphorus loads therefore, are considered to be the loads emanating from urban lands within US Census Bureau-designated “urban boundaries”. These boundaries are depicted in Figure 7-1, and identify portions of the municipality of Clearlake that discharge to the Clear Lake waterbody. Phosphorus loads from these areas were determined in the same manner as other nonpoint loads. Again, for purposes of the TMDL, these loads will be presented as Waste Load Allocations, even though they are non-discrete in nature. They are presented as WLAs due to the fact that they are associated with a permit.

Landuses in areas designated as “urban” by the U.S. Census Bureau are shown in Table 7-1. Urban landuses are shaded and extend over multiple modeled subwatersheds. For example, portions of Clearlake are located in subbasins 1, 2, 3, and 37. For allocation purposes, the appropriate loads will be applied to the related subbasin.

Table 7-1. MRLC Landuse categories within Phase II MS4 Urban Boundaries

Category	Total within Clearlake Municipality (ac)	Draining to Clear Lake (ac)
Open Water	160	136
Low Intensity Residential	1179	860
Commercial/Industrial/Transportation	133	108
Bare Rock/Sand/Clay	4	2
Transitional	118	91
Decidiuous Forest	81	58
Evergreen Forest	535	365
Mixed Forest	607	455
Shrubland	847	571
Planted/Cultivated (orchards, vineyards, groves)	<1	0
Grasslands/Herbaceous	1138	832
Pasture/Hay	291	0
Emergent Herbaceous Wetlands	<1	0
Total (square meters)	5095	3478
Subbasins		*1, 2, 3, 37*

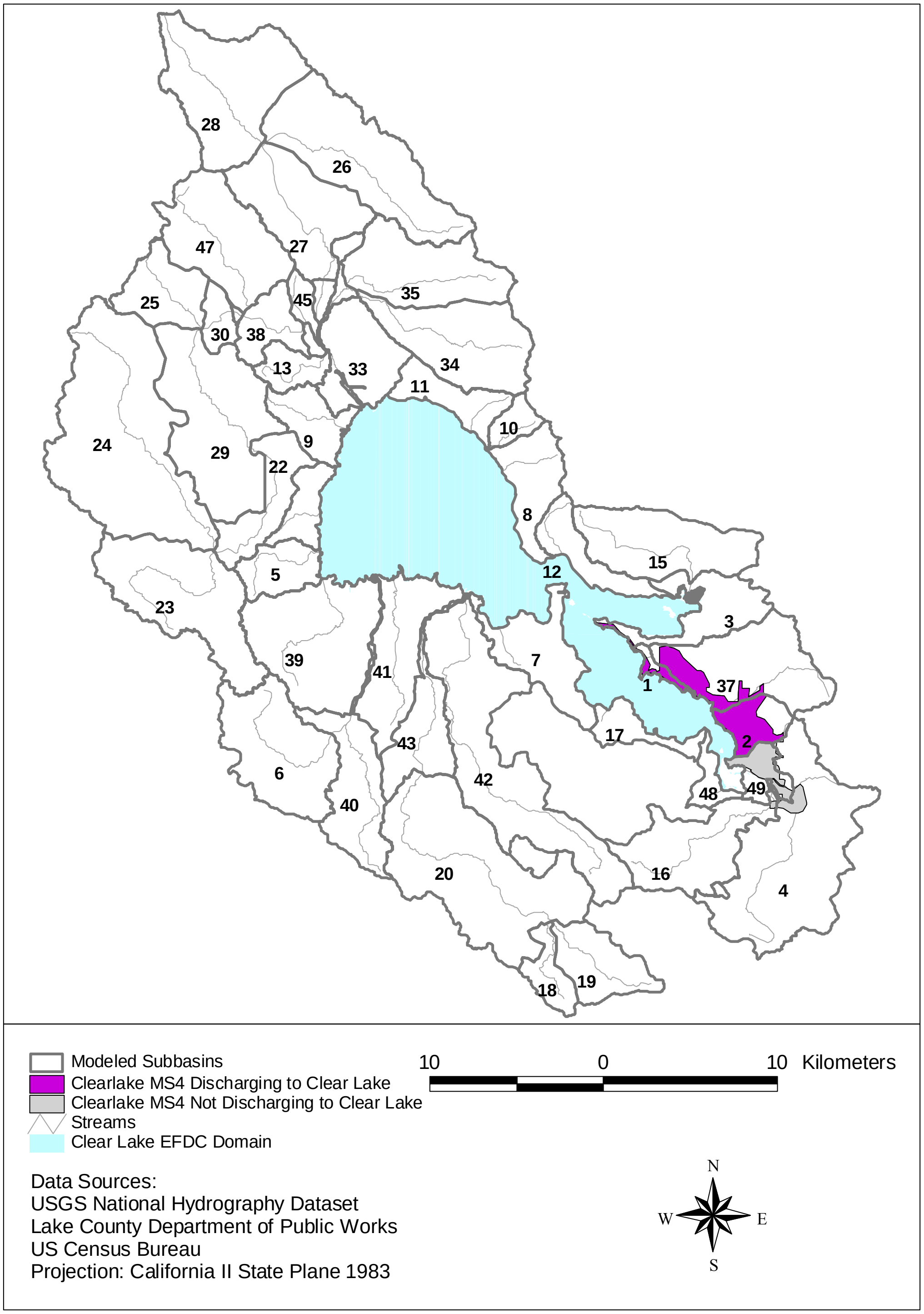


Figure 7-1. Urban boundaries associated with MS4 permits

7.2 Load Allocations

A chlorophyll-a concentration of 73 ug/L, which represents the maximum of summer peak concentrations for "compliant" years, was assigned as the TMDL target not to be exceeded at the CL1 monitoring location. As described in Section 2.2, "compliant" years are years where the lake was merely green during the summer but significant amounts of noxious blue green algal scum were not recorded. Due to reports of scum present in large quantities during the 1990-91 bloom in addition to just being discolored, the summers during these years exhibited conditions that were not compliant. Figure 7-2 illustrates chlorophyll-a results for the existing condition, upon which the maximum chlorophyll-a concentration was derived. The maximum chlorophyll-a concentration for the years 1985-1989 ("compliant" years) was 73 ug/L and occurred on June 16th, 1989.

The critical concentration of chlorophyll-a was estimated by the modeling system (discussed in Section 6) developed for calculating the TMDL, which was used to evaluate trends in chlorophyll-a at seasonal, annual, and multi-year scales. A reduction of external phosphorus loading was the scenario employed to control the magnitude of simulated chlorophyll-a concentrations.

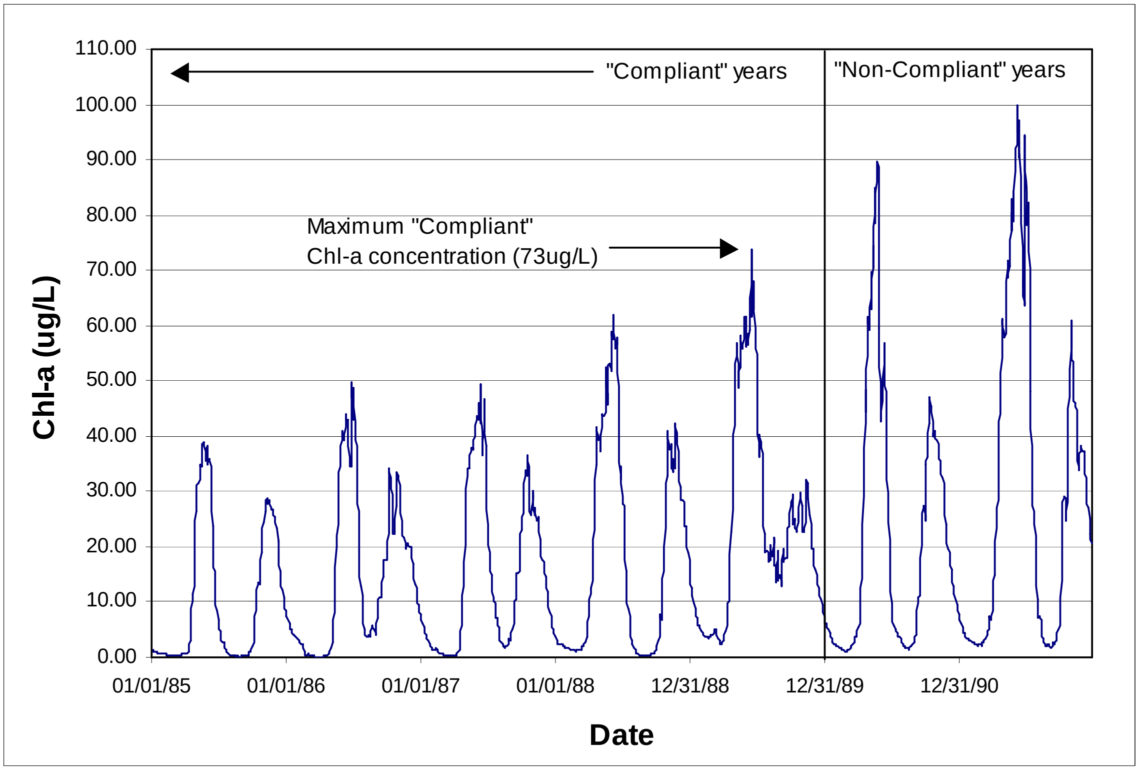


Figure 7-2. Simulated Chlorophyll-a Concentration Trends during "Compliant" (1985-1989) and "Non-compliant" (1990-1991) years.

7.3 Existing Loading

Existing conditions were estimated by simulating the current land use distribution, as described in the MRLC dataset. Phosphorus loads from 6 regions of the watershed were obtained from the watershed model upon which to calculate the load reductions required to attain the in-lake chlorophyll-a target of 73 ug/L. Major drainage areas, such as the watershed draining to Rodman Slough (subbasin 33), are delineated as a region. Other streams discharging to Clear Lake that do not drain significant upstream areas were grouped as “intermediate” regions which are allocated to as a whole. The delineation of these regions is shown in Figure 7-3. The average daily load of phosphorus during the 1985-1991 period, as calculated by the modeling system, was 411 kg/day.

7.3.1 Scenario Runs

A number of scenarios were simulated by the modeling system in an effort to; (a) identify the range of potential conditions in Clear Lake, and (b) identify a phosphorus loading reduction that would allow Clear Lake to meet the TMDL target, and therefore attain its beneficial uses. A scenario was first developed to estimate land use change impacts in the Clear Lake watershed, in an effort to define the natural range of behavior in Clear Lake. Although this scenario represented pre-European land use patterns (e.g removal of agricultural and urban land parcels), the influence of anthropogenic modifications such as the removal of significant wetland features and channel modification have not been quantified, and thus, were not simulated. Therefore, the nutrient reduction capacities of these wetlands and impoundments that existed prior to settlement are not represented, and the pre-European scenario estimates loading regimes based on land use change only.

The average daily external load of phosphorus in the pre-European land use distribution scenario was 370 kg/day, or a 10% reduction in phosphorus compared to the existing condition. This reduction in phosphorus loading was not sufficient to meet the TMDL target of 73ug/L, so additional scenarios were developed to identify the reduction required to attain this target.

Figure 7-4 illustrates the maximum annual chlorophyll-a concentrations for existing loading conditions, as well as for scenarios characterized by 25% and 40% reductions in phosphorus loading. The average daily phosphorus loading rates for each of the scenarios are 411 kg/day, 308 kg/day, and 247 kg/day for the existing, 25% reduction, and 40% reduction scenarios, respectively. Figure 7-4 illustrates that the only scenario that attains the TMDL target of 73 ug/L is the scenario where a 40% reduction in phosphorus is applied. In this scenario, a maximum concentration of 64.9 ug/L occurs in 1991.

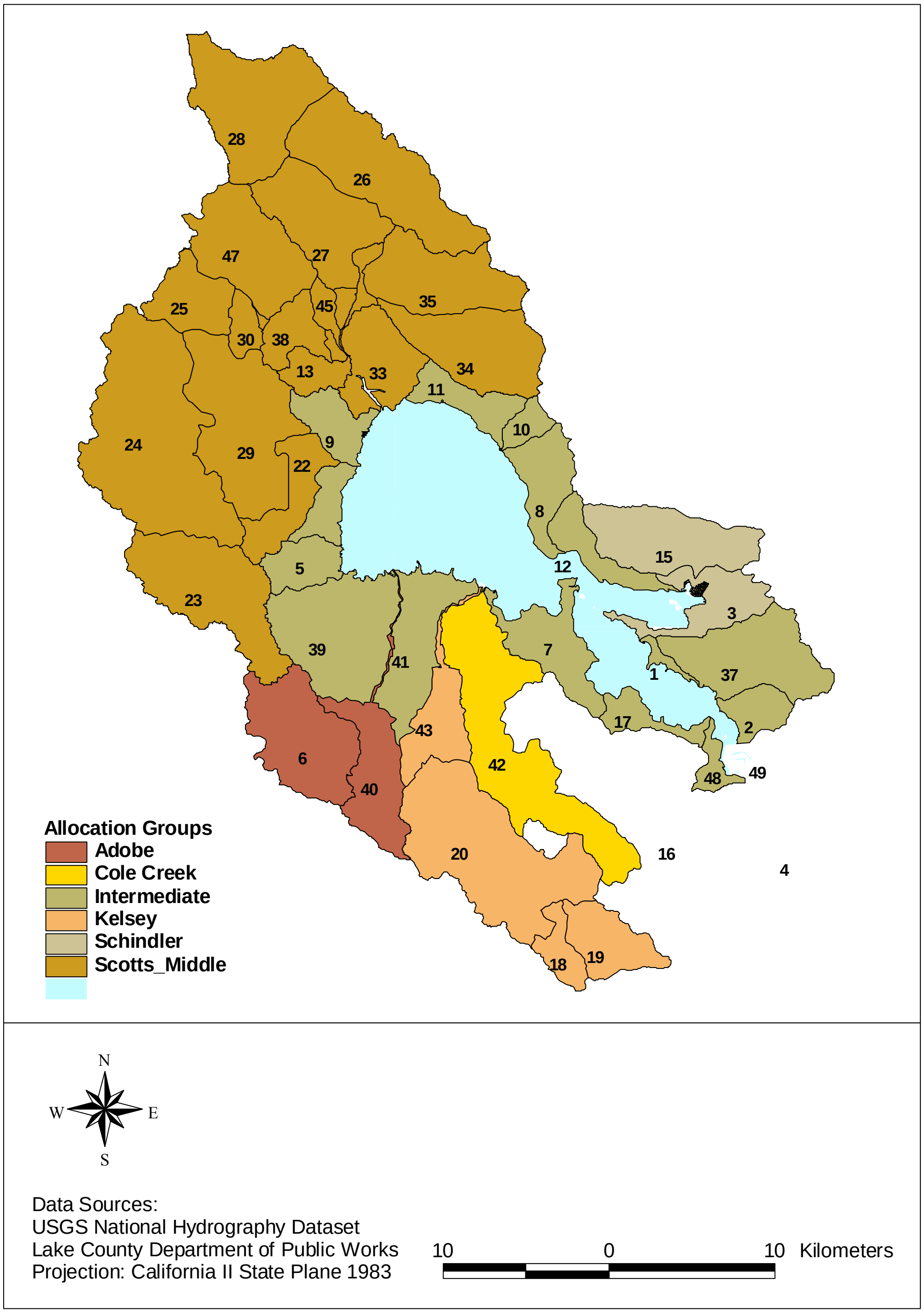


Figure 7-3. Allocation Groups in the Clear Lake watershed.

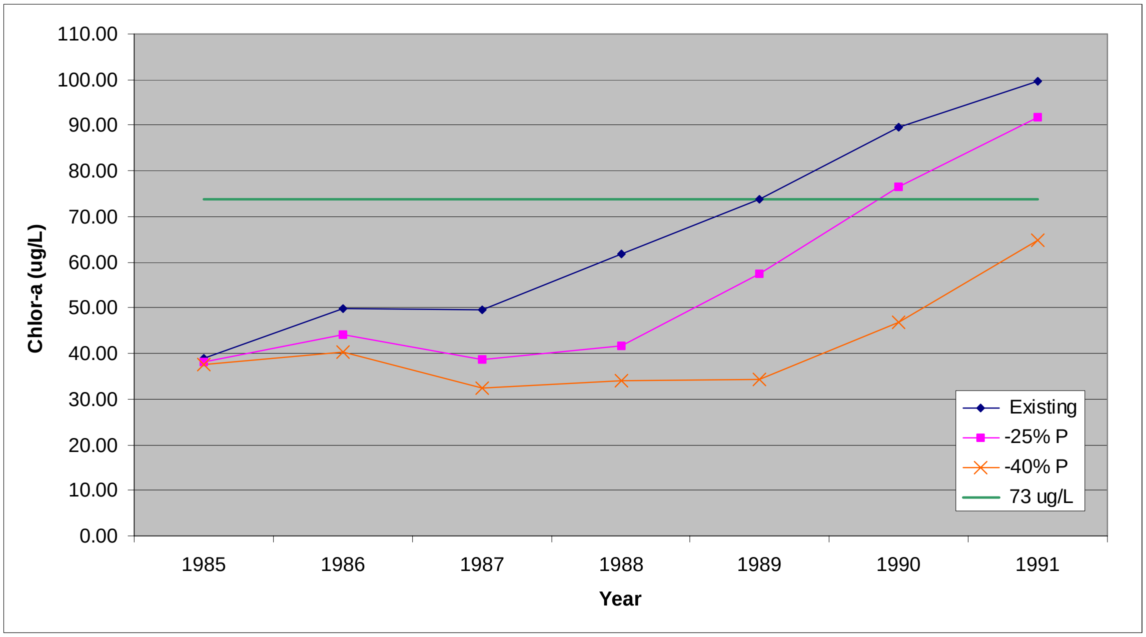


Figure 7-4. Annual Peak Chlorophyll-a Concentrations from Scenario Runs.

Based on these scenario runs, a scenario where land use patterns are modified to represent pre-European distributions, but with a current representation of stream channel diversions and modifications, does not attain the chlorophyll-a target of 73 ɥg/L for the 1985-1991 time period. Scenario runs with reduced loadings of phosphorus limit algal productivity, with a 40% reduction in external phosphorus loading allowing for attainment of the chlorophyll-a target. As shown in Figure 7-4, a 40% reduction in external phosphorus loading meets the TMDL target with a maximum chlorophyll-a concentration of 64.9 ug/L, providing a margin of safety of 8 ug/L (see Section).

A reduction of 40% was shown not to be possible as a result of as a result of land use-based BMPs alone, as demonstrated by the pre-European scenario. Instead, as cited in the Clean Lakes Report (Lake County/UCD Clean Lakes Project: Final Report, July 1994) and other research (Goldstein and Tolsdorf, 1994), stabilization and restoration of wetlands critical to removing sediment-associated phosphorus must supplement land use-based BMPs if a 40% reduction is to be achieved.

7.4 Allocation Methodology

Although phosphorus loading to Clear Lake is naturally high, increased loads associated with anthropogenic activities have been implicated in contributing to water quality degradation and subsequent algal productivity. Therefore, it is these sources that are targeted for loading reductions. The majority of phosphorus loading reductions were applied to watersheds with the potential for wetlands restoration. Reclamation and removal of natural wetlands is cited as having a significant impact on phosphorus loading to Clear Lake. For example, the Middle Creek Flood Damage Reduction and Ecosystem Restoration Project aims to reconnect Scotts Creek and Middle Creek to the historic Robinson Lake wetlands and floodplain. A 40% reduction in the sediment-associated phosphorus load from Scotts Creek is anticipated if the project is undertaken, and the allocations take this into account by assigning a higher phosphorus reduction to that watershed (60% to the Scotts/Middle Allocation Group) relative to other watersheds in the Clear Lake system.

Allocations and reductions were also based in part on land use distributions in the allocation group as represented by the MRLC land use coverage. In addition to existing land uses, unpaved road-related features are also significant phosphorus sources in the Clear Lake watershed (Goldstein and Tolsdorf, 1994), and were considered in the allocation strategy. Table 7-2 shows the existing loads and TMDL loads from each of the allocation groups. Although a 40% reduction in phosphorus loading achieves the TMDL target, a 41.9% reduction is represented by the total TMDL loading rate for phosphorus shown in Table 7-2. The additional 1.9% reduction in loading is a result of the coarse allocation methodology and may be considered an explicit margin of safety.

The TMDL loads represent reductions in external phosphorus loading due to potential wetlands restoration and stream channel stabilization efforts, in addition to areas identified as significant sources of sediment-associated phosphorus (e.g regions characterized by dense agriculture, logging road networks, channel instability due to a history of gravel mining). The following paragraphs describe the general allocation strategies followed for specific subwatersheds in the Clear Lake watershed.

Table 7-2. Existing and TMDL loading rates by Allocation Group.

Watershed Group	Existing TP Loading (kg/day)	% Total Phosphorus Loading to Clear Lake	TMDL Loading (kg/day)	Percent Reduction
Intermediates*	126.04	23%	81.93	35
Schindler	26.79	5%	21.43	20
Scotts/Middle	169.55	30%	67.82	60
Adobe	30.06	5%	22.55	25
Cole	23.20	4%	18.56	20
Kelsey	35.74	6%	26.80	25
Total:	411.39		239.10	

7.4.1 Scotts Creek/Middle Creek Watershed (modeled subbasins 12, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 37, 43, 44, 45, and 46)

The Scotts Creek/Middle Creek watershed is steep in upland areas, naturally highly erodable, influenced by agriculture in flatter areas such as Scotts Valley, and subject to substantial mass wasting events. Many landslide features are present, including significant features influential enough to change drainage patterns and watershed boundaries (i.e a landslide blocked an outlet to the Russian River near Blue Lakes approximately 10,000 years ago). Agriculture is present along the Scotts Valley, and there are orchards along the stream in lower portions of the watershed.

Allocation Strategy:

The Scotts Creek/Middle Creek watershed was allocated to as a whole, based on the degree of anthropogenic influence and the potential for achieving load reductions. The largest load reductions are from this watershed. Potential reductions of phosphorus loading to Clear Lake as a result of the Robinson Lake restoration project have been estimated at 40%. The modeling system estimated that this watershed contributed 41% of the total phosphorus load to Clear Lake during the 1985-1991 period. A reduction in phosphorus loading of 60% is required from this watershed, based on the potential for the restoration of Robinson Lake and significant agricultural and forest road acreage.

7.4.2 Adobe Creek Watershed (modeled subbasins 6 and 40)

The Adobe Creek watershed is steep in upland areas, naturally highly erodable, influenced by agriculture in downstream portions of the watershed. Diversions in the downstream sections and its proximity to Kelseyville characterize this watershed.

Allocation Strategy:

The Adobe Creek watershed was allocated to as a whole, based on the degree of anthropogenic influence and the potential for achieving load reductions. The modeling system estimated that this watershed contributed 7% of the total phosphorus load to Clear Lake during the 1985-1991 period. A reduction in phosphorus loading of 25% is required from this watershed, based on the potential for restoration and significant agricultural and forest road acreage.

7.4.3 Cole Creek Watershed (modeled subbasin 42)

The Cole Creek watershed is partially delineated by Mt. Konocti, is naturally highly erodable, and is influenced by agriculture in downstream portions of the watershed. Its proximity to Kelseyville characterize this watershed.

Allocation Strategy:

The Cole Creek watershed was allocated to as a whole, based on the degree of anthropogenic influence and the potential for achieving load reductions. The modeling system estimated that this watershed contributed 4% of the total phosphorus load to Clear Lake during the 1985-1991 period. A reduction in phosphorus loading of 20% is required from this watershed, based on the potential for improvement and land use distribution.

7.4.4 Kelsey Creek Watershed (modeled subbasins 43,20,18 and 19)

The upstream portion of the Kelsey Creek watershed is dominated by forested and shrubland, while downstream portions are impacted by Kelseyville and cropland and pasture associated with it. The watershed is naturally highly erodable, and is influenced by agriculture in downstream portions of the watershed.

Allocation Strategy:

The Kelsey Creek watershed was allocated to as a whole, based on the degree of anthropogenic influence and the potential for achieving load reductions. The modeling system estimated that this watershed contributed 6% of the total phosphorus load to Clear Lake during the 1985-1991 period. A reduction in phosphorus loading of 25% is required from this watershed, based on the potential for improvement and land use distribution.

7.4.5 Schindler Creek Watershed (modeled subbasins 3 and 15)

The Schindler Creek watershed discharges to Oaks Arm in the Clearlake Oaks region, after draining the agricultural area of High Valley. Downstream portions are impacted by Clearlake Oaks. The watershed is naturally highly erodable, and is influenced by urbanization in downstream portions of the watershed.

Allocation Strategy:

The Schindler Creek watershed was allocated to as a whole, based on the degree of anthropogenic influence and the potential for achieving load reductions. The modeling system estimated that this watershed contributed 5% of the total phosphorus load to Clear Lake during the 1985-1991 period. A reduction in phosphorus loading of 20% is required from this watershed, based on the potential for improvement and land use distribution.

7.4.6 Intermediate Watersheds (modeled subbasins 5, 2, 8, 9, 41, 7, 11, 1, 10, 14, 39, 48, 17, 12, and 37)

The Intermediate watershed group discharges to all three arms of Clear Lake, and are generally characterized by smaller drainage areas along the shoreline. These subbasins are characterized by moderate (i.e Lakeport, Lucerne, Soda Bay, Nice) and low-impact (i.e individual, detached housing) shoreline development. These watersheds are influenced by anthropogenic sources and contribute directly to the lake due to a lack of attenuation.

Allocation Strategy:

The intermediate watershed group was allocated to as a whole, based on the degree of anthropogenic influence and the potential for achieving load reductions. Rehabilitation of tule marsh and wetland areas along the shoreline was cited as a strategy in filtering nutrients from entering the open lake, and the intermediate watersheds include the majority of the Clear Lake shoreline. The modeling system estimated that this watershed group contributed 49% of the total phosphorus load to Clear Lake during the 1985-1991 period. A reduction in phosphorus loading of 35% is required from this watershed group, based on the potential for improvement, current contributions of phosphorus, and land use distribution.

7.5 Margin of Safety

There are two methods for incorporating the MOS (USEPA, 1991):

- Implicitly incorporate the MOS using conservative model assumptions to develop allocations.
- Explicitly specify a portion of the total TMDL as the MOS and use the remainder for allocations.

For the Clear Lake nutrient TMDL, explicit and implicit MOS were incorporated in several ways. Although a 40% reduction in watershed phosphorus loading was found to achieve the TMDL target, the allocation methodology resulted in a 41.9% reduction of phosphorus. The additional 1.9% reduction in watershed loads is considered an explicit margin of safety for the Clear Lake TMDL. A 40% reduction in phosphorus meets the TMDL target of 73 ug/L by producing a maximum concentration of 64.9 ug/L. This 8 ug/L buffer also provides an explicit margin of safety for the TMDL to be met.

The use of a multiple-year drought simulation period (1986 to 1992) enabled the consideration of the critical condition and cause of the impairment of Clear Lake. Although a range of conditions were represented by this time period, it contained two summers exhibiting algal blooms characteristic of the worst conditions in Clear Lake.

Throughout the TMDL development process, conservative assumptions were made. For example, chlorophyll-a concentrations associated with the selected target may be conservative with respect to the high productivity that occurs naturally in the Clear Lake watershed, since the chlorophyll-a concentration target was based on peak levels from a relatively dry year. The target was selected to be protective of the beneficial uses (Recreation 1,2; Warm Freshwater Habitat; Warm Water Spawning).

8 IMPLEMENTATION

The CVRWQCB will add text here on implementation.

REFERENCES

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, A.S. Donigian, and R.C. Johanson. 1996 *Hydrological Simulation Program – FORTRAN (HSPF): User's Manual Release 11*. Environmental Research Laboratory, Office of Research and Development, USEPA, Athens, Georgia.

Cerco, C. and T. Cole. 1994. *Three-Dimensional Eutrophication Model of Chesapeake Bay*. Technical Report EL-94-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

CVRWQCB (Central Valley Regional Water Quality Control Board). 1998. *Water Quality Control Plan for the Sacramento and San Joaquin River Basins (5A/5B)*. Central Valley Regional Water Quality Control Board, Sacramento, CA.

Goldstein, J.J., and T.N. Tolsdorf, 1994. An Economic Analysis of Potential Water Quality Improvement in Clear Lake: Benefits and Costs of Sediment Control, Including a Geological Assessment of Potential Sediment Control Levels. USDA Soil Conservation Service Davis and Lakeport Offices.

Hinton, R.N., 1972. Clear Lake Recreation. Appendix D. Alternative Eel River Projects and Conveyance Routes. Red Bluff: DWR Northern Division.

Reckhow, K.H., and S.C. Chapra, 1983. Engineering Approaches for Lake Management: Vol. 1. Data Analysis and Empirical Modeling, Butterworth Publishers, Boston.

Richerson, P.J., T.H. Suchanek, and S.J. Why 1994, The Causes and Control of Algal Blooms in Clear Lake, Clean Lakes Diagnostic/Feasibility Study for Clear Lake, California. Report prepared for Lake County Flood Control and Water Conservation District, California Department of Water Resources, and United States Environmental Protection Agency.

Sun J, Liu D Y. 2003. Geometric models for calculating cell biovolume and surface area for phytoplankton. *Journal of Plankton Research*, in press.

USEPA (United States Environmental Protection Agency). 1991. *Guidance for Water Quality-Based Decisions: The TMDL Process*. EPA 440/4-91-001. United States Environmental Protection Agency, Office of Water, Washington, DC.

USEPA (United States Environmental Protection Agency). 1996. Hydrologic Simulation Program- FORTRAN (HSPF). Release 11. United States Environmental Protection Agency, Office of Water, Washington, DC.

USGS EROS Data Center (2000) *MRLC Regional Land Cover Characterization Project*. Multi-Resolution Land Characteristics Consortium National Land Cover Data Program.

APPENDIX A: WATERSHED HYDROLOGY CALIBRATION AND VALIDATION

The following pages present graphs comparing model runs versus observed flow data for the calibration period (October 1, 1992 to September 30, 1993) at the three gaged locations in the Clear Lake watershed. Water year 1993 was used for calibration because in addition to water quality sampling data, phosphorus loading from Scotts, Middle, and Kelsey Creeks was calculated for that water year, and provides additional calibration data. Water quality calibration will be discussed in Appendix C. Water year 1993 was a relatively wet year, with over 50 inches of rainfall recorded in Lakeport (average rainfall is 33.5 inches annually, based on 31 years of record). The validation period of 10/1/1993-9/30/1995 was characterized by years experiencing between 33.2 (about average) and 60.1 (highest on record) inches of annual rainfall.

Although data obtained from local weather stations were used in this modeling effort, localized rainfall events were not always reflected in actual rainfall recorded data. This resulted in discrepancies between modeled and observed flow for various storms through the validation time period. Specifically, rainfall timing and intensity may not be accurately represented for January and February of 1995 at all three gaged locations, where rainfall at these locations may be underestimated in the simulation. In addition, weather data required to simulate lake hydrodynamics were not readily available from local stations, and were obtained from other stations in the region.

It is apparent from the flow duration curves that the model slightly overpredicts summer baseflow in the stream. Although the summer months represent the critical period with respect to algal blooms, the discrepancy in flows is less than 5 cfs. This overprediction of baseflow is not significant relative to annual flows, and does not have a significant effect on nutrient loading to Clear Lake. Gaps in the Middle Creek observed flow dataset also appear to be an overestimation in modeled flows for both the calibration and validation periods. These data gaps include the periods of 12/29/92-1/18/93, 1/8/95-1/19-95, 2/8/95-3/5/95, and 6/8/95-6/22/95. Similar data gaps do not exist for the Scotts and Kelsey Creek stations.

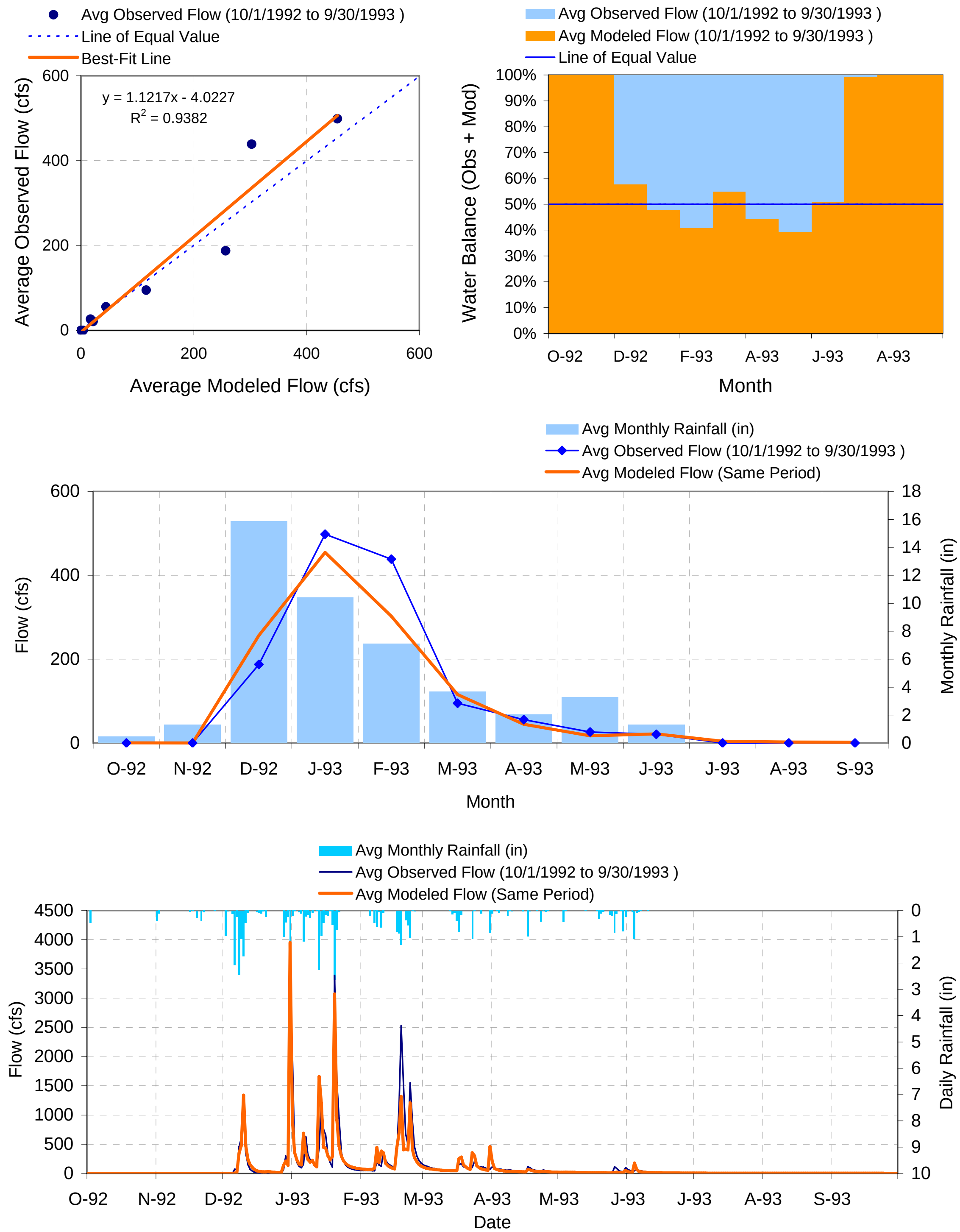


Figure A-1. Hydrology calibration results at the DWR Scotts Creek (SCR) gage.

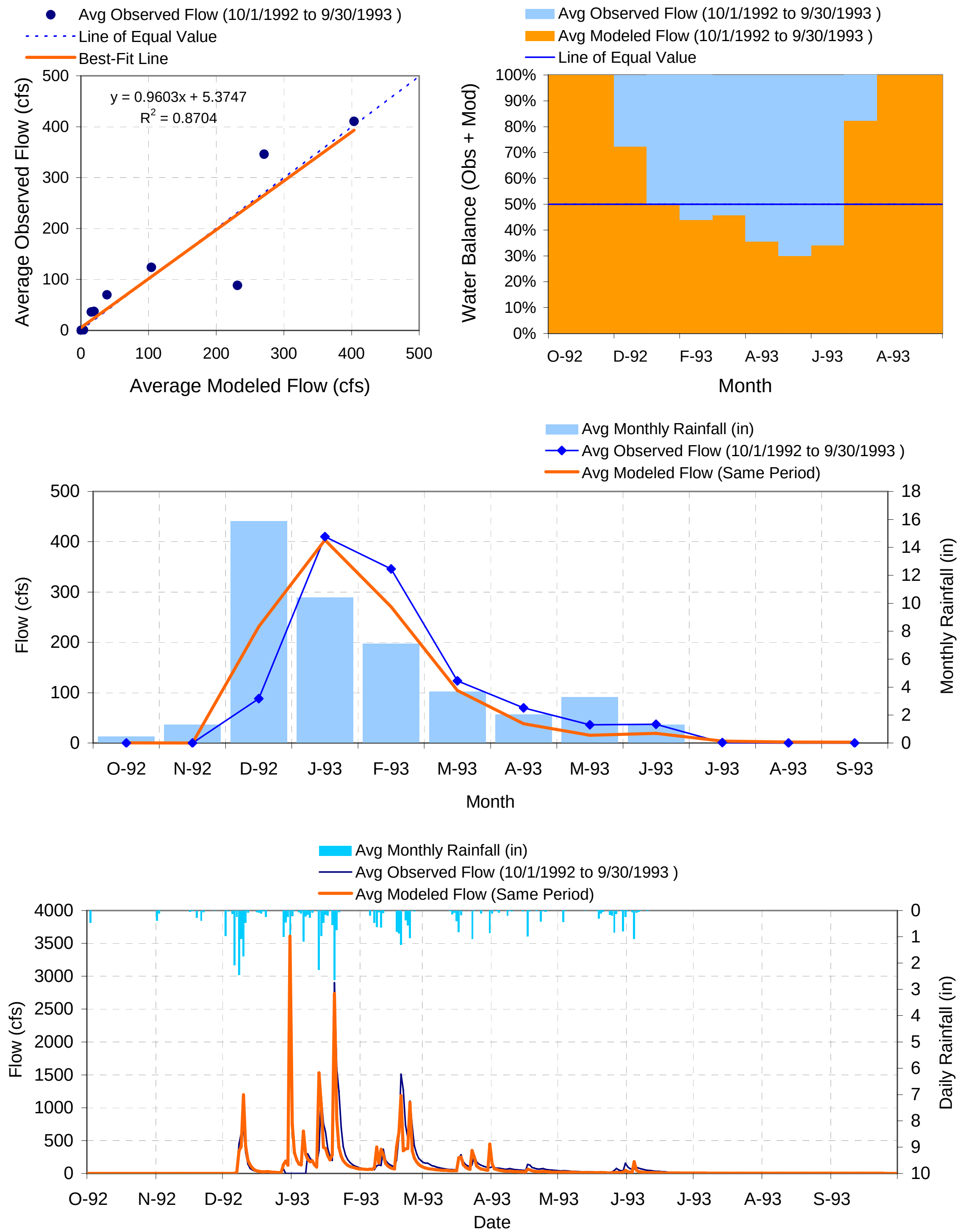


Figure A-2. Hydrology calibration results at the DWR Middle Creek (MCK) gage.

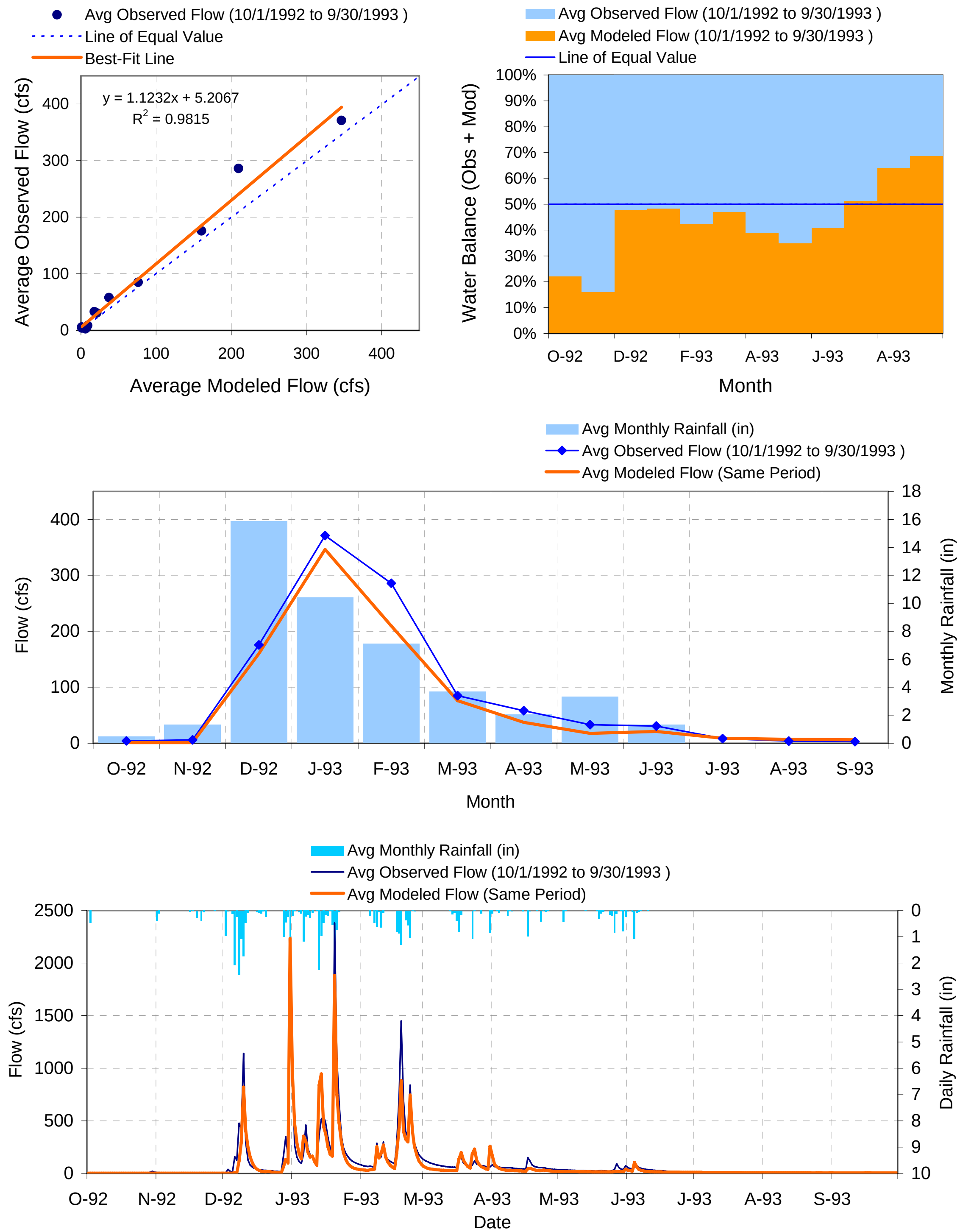


Figure A-3. Hydrology calibration results at the DWR Kelsey Creek (KEL) gage.

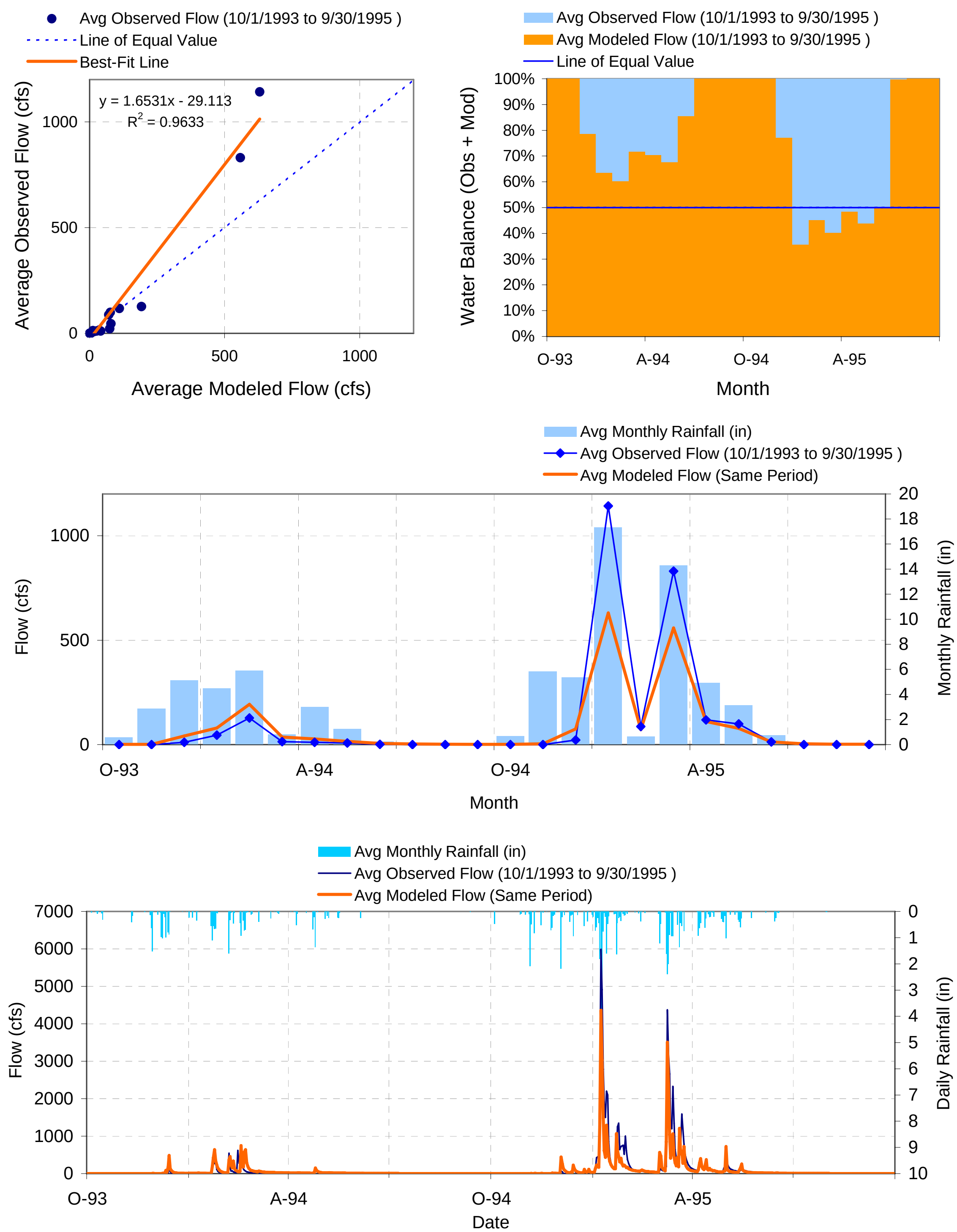


Figure A-4. Hydrology validation results at the DWR Scotts Creek (SCR) gage.

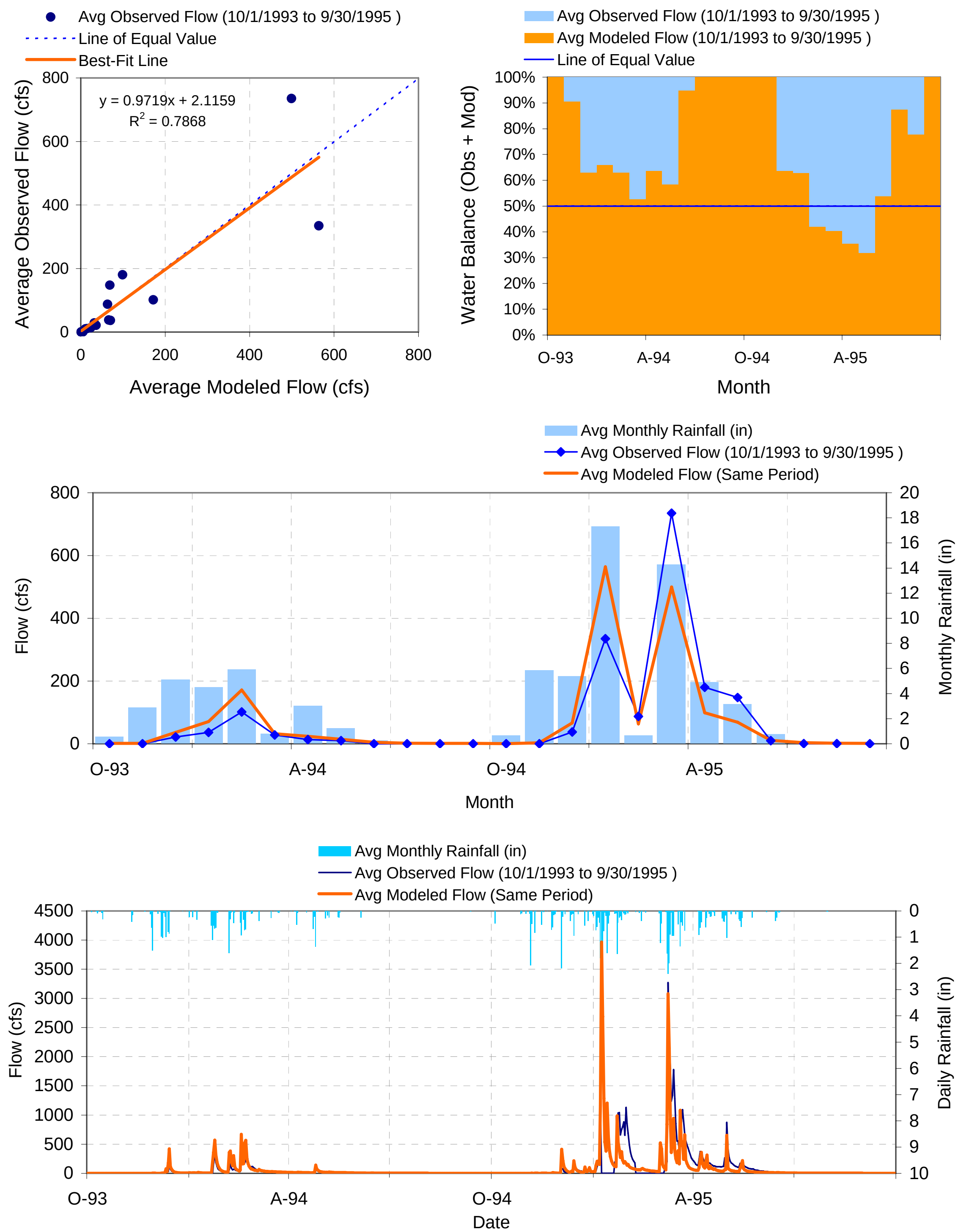


Figure A-5. Hydrology validation results at the DWR Middle Creek (MCK) gage.

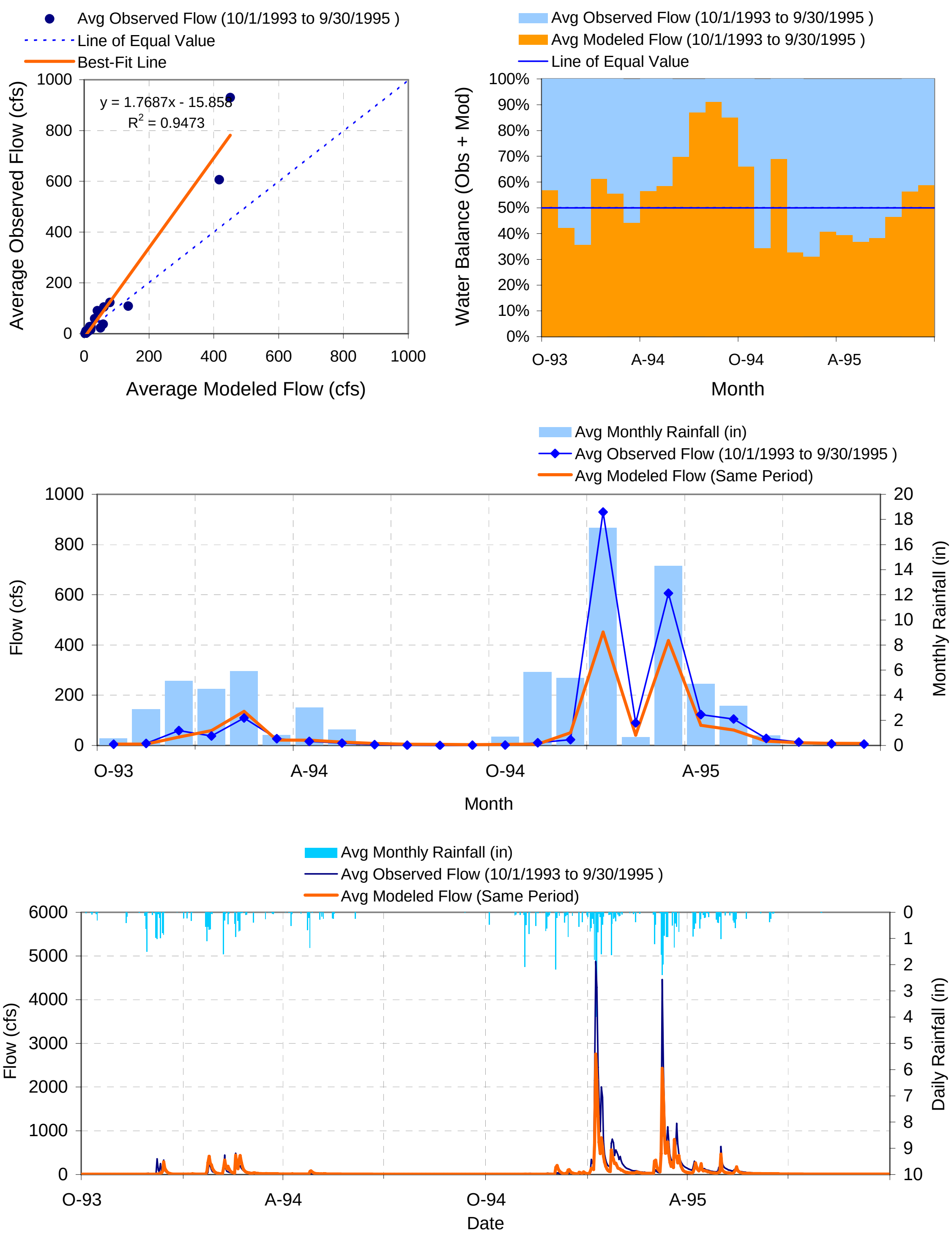


Figure A-6. Hydrology validation results at the DWR Kelsey Creek (KEL) gage.

APPENDIX B: LAKE HYDRODYNAMIC CALIBRATION AND VALIDATION

The following pages present graphs comparing receiving water model runs versus observed stage data for the calibration period (January 1, 1997 to December 31, 1997) at the Clear Lake at Lakeport (CLK) gage. This time period was used for calibration because 1997 is the first year that daily stage data is available, and watershed flow data is not available after 5/31/1996, so calibration periods for the watershed and hydrodynamic models do not coincide. However, the independent successes of the watershed and lake calibrations suggest that both models are representing the system reasonably well. The year 1997 is also characterized by relatively average annual rainfall totals (37.39 inches) measured at the Lakeport (4701) station, relative to an average annual rainfall total of 33.52 inches of rainfall annually. The period of 1/1/1995-12/31/1996 was selected for the validation period. 1995 and 1996 were used as validation years. Temperature data from three in-lake monitoring stations were used to validate the model for this time period. Above-average annual rainfall totals characterize both 1995 and 1996 (65.08 and 46.04 inches, respectively). Calibration and validation plots are shown in figures B-1 and B-2.

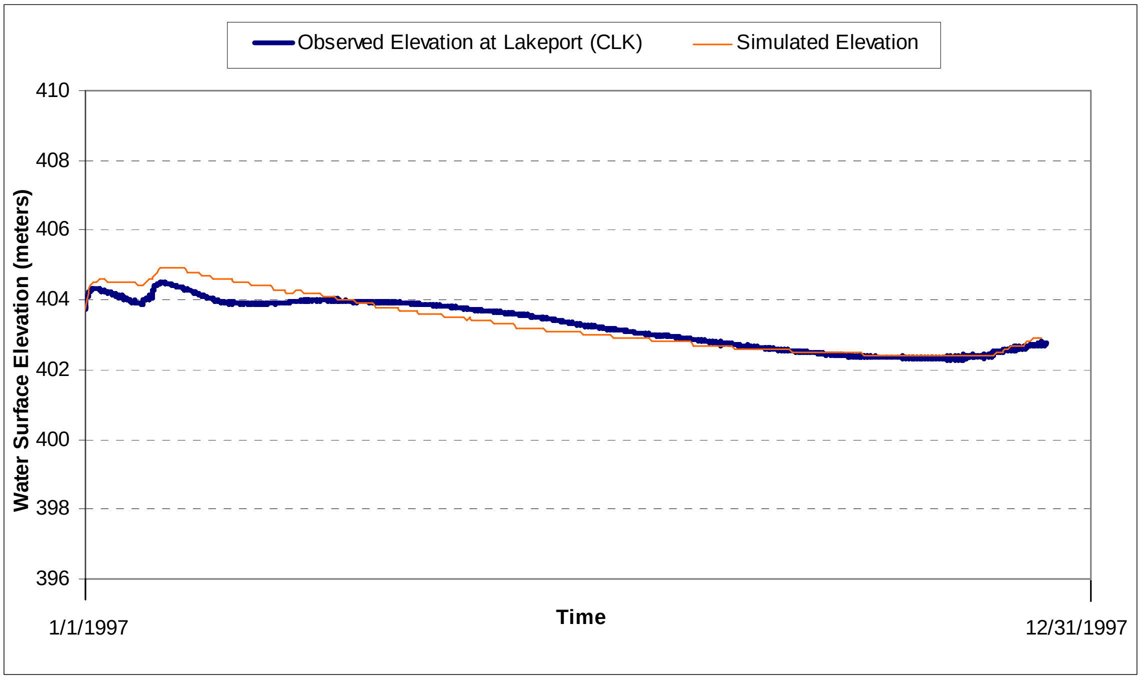


Figure B-1. Water Surface Elevation calibration results at the Clear Lake at Lakeport (CLK) gage.

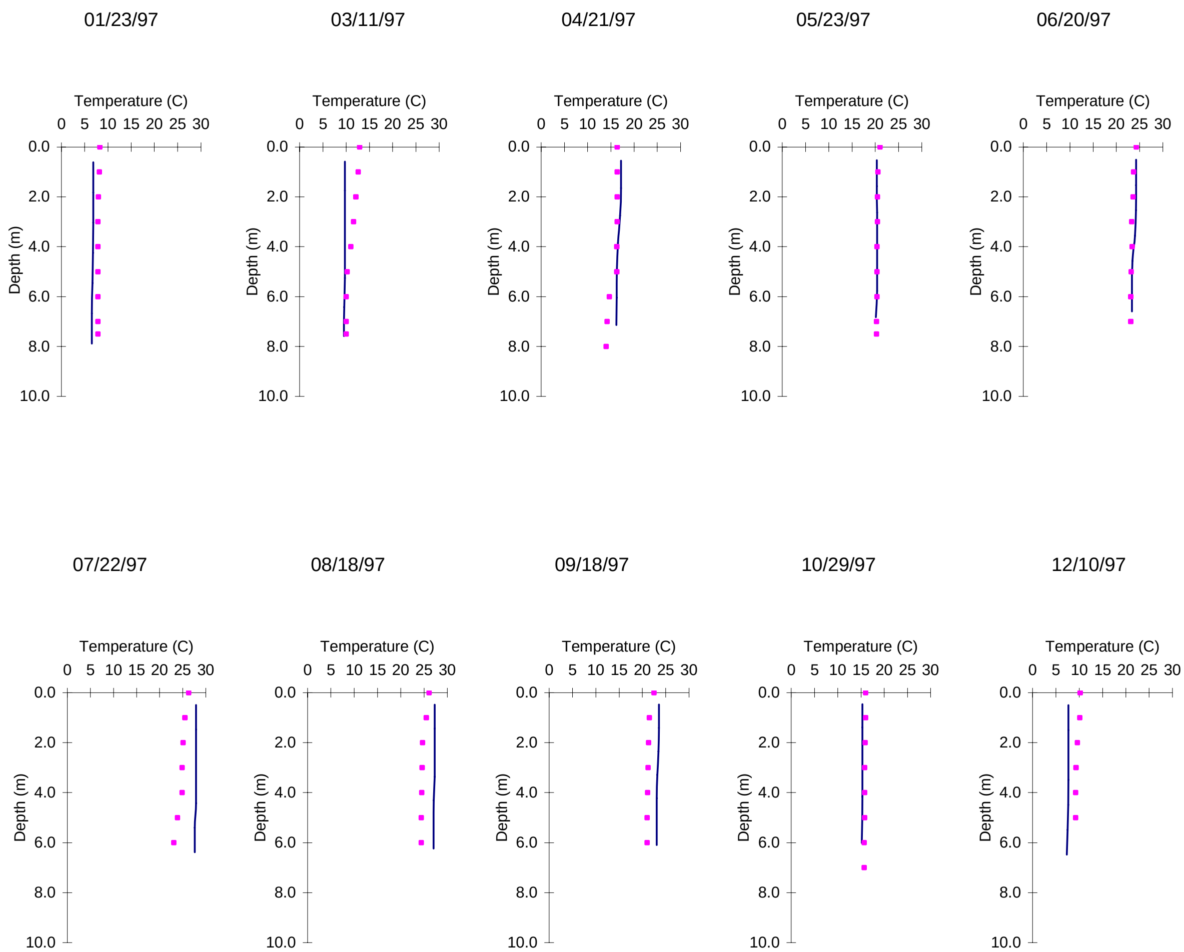


Figure B-2. Temperature calibration results at the Upper Arm (CL1) station (points are observed data, lines are simulated data).

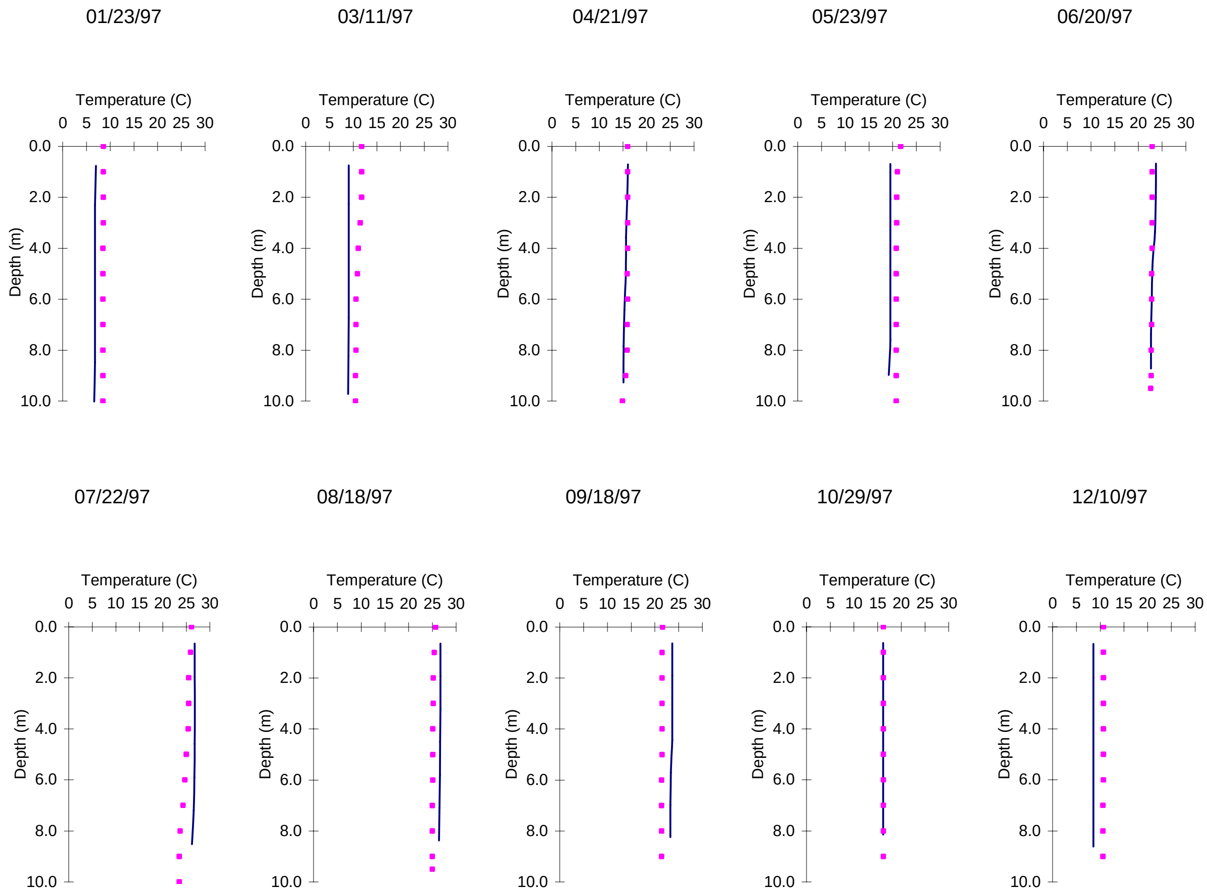


Figure B-3. Temperature calibration results at the Lower Arm (CL3) station (points are observed data, lines are simulated data).

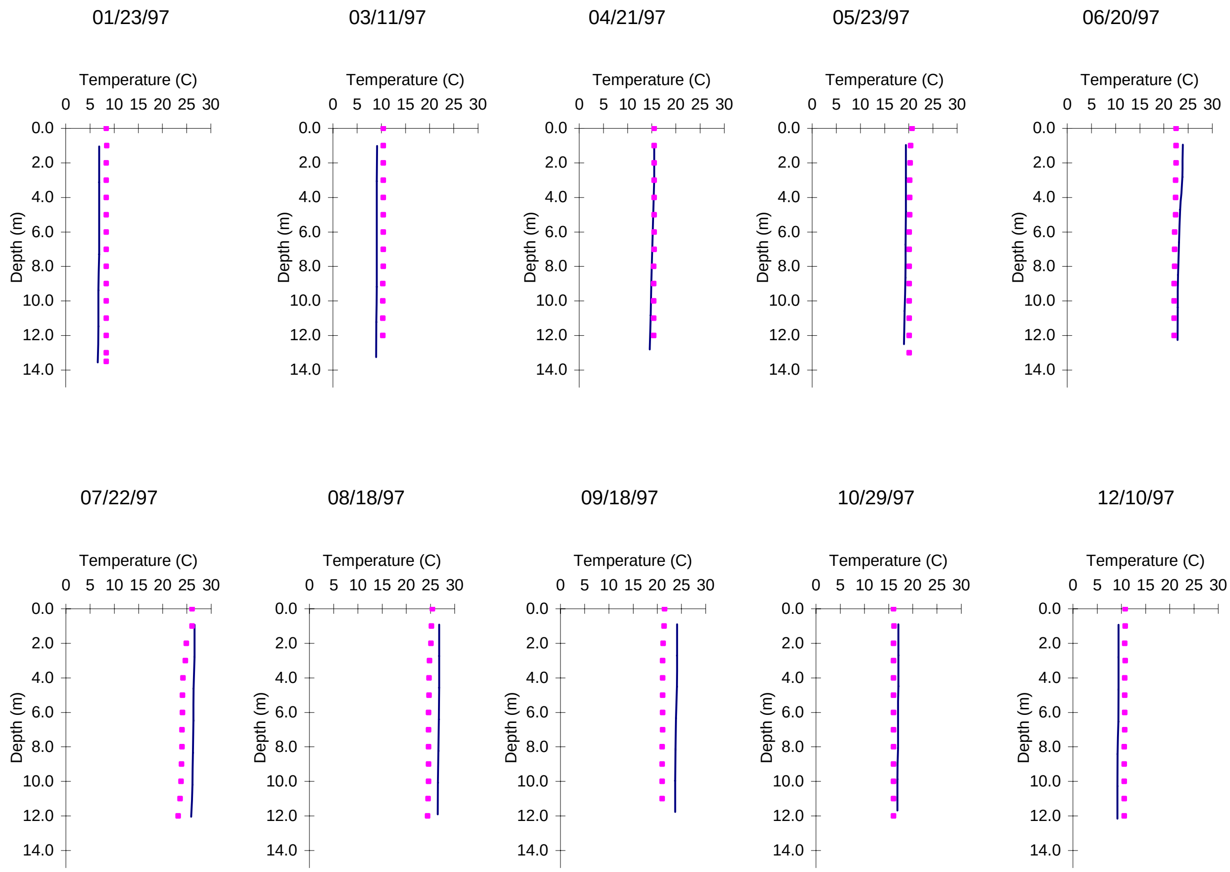


Figure B-4. Temperature calibration results at the Oaks Arm (CL4) station (points are observed data, lines are simulated data).

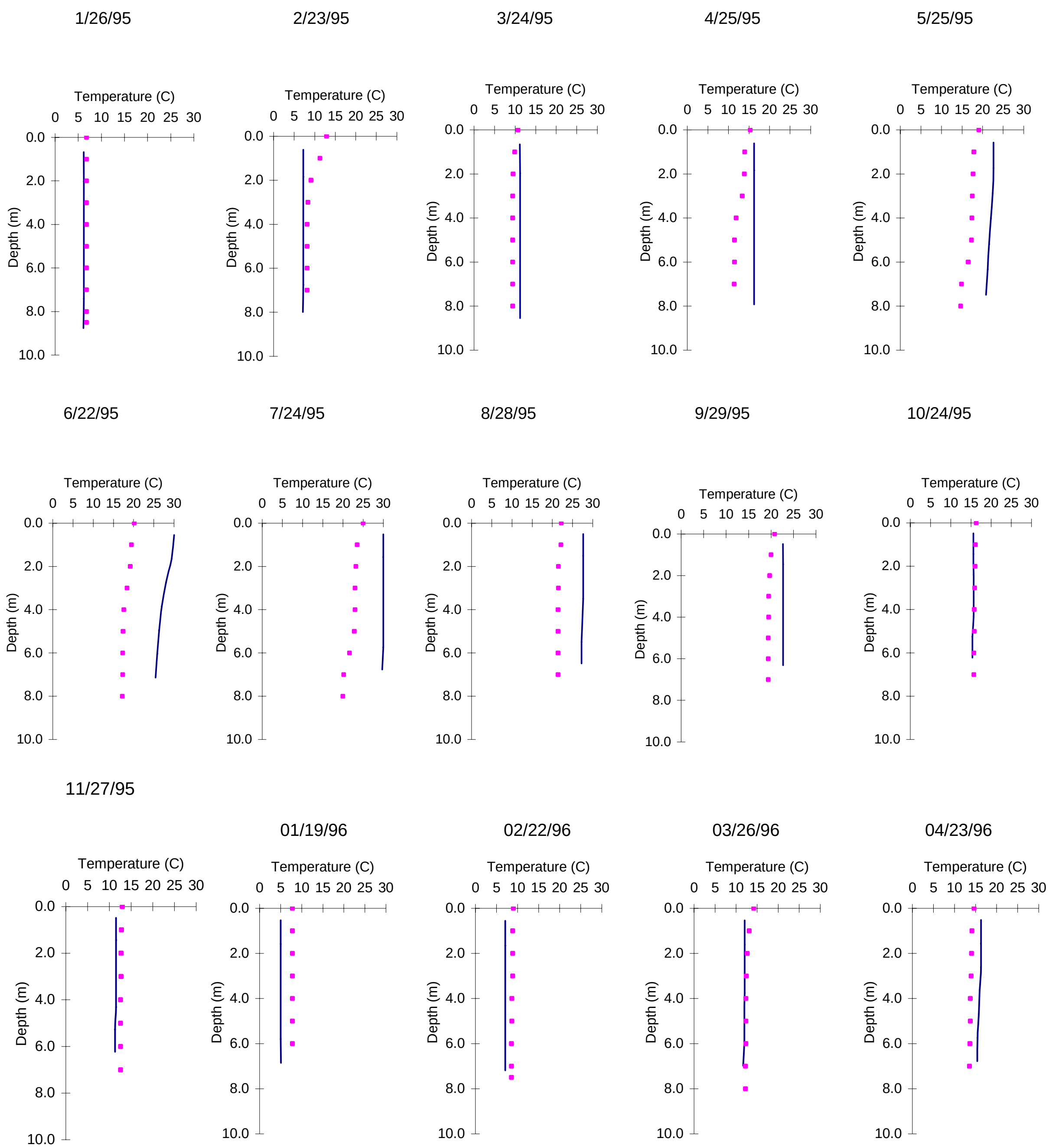


Figure B-5. Temperature calibration results at the Upper Arm (CL1) station (points are observed data, lines are simulated data).

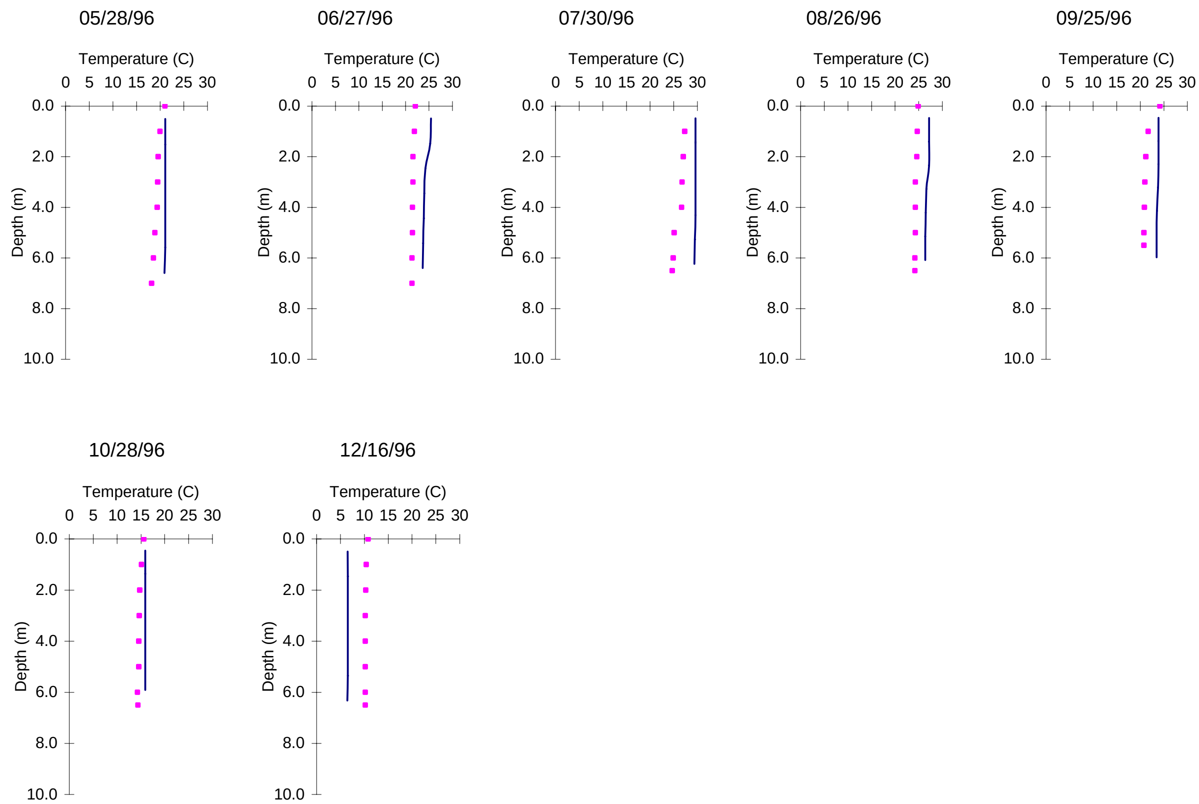


Figure B-5 (Continued). Temperature calibration results at the Upper Arm (CL1) station (points are observed data, lines are simulated data).

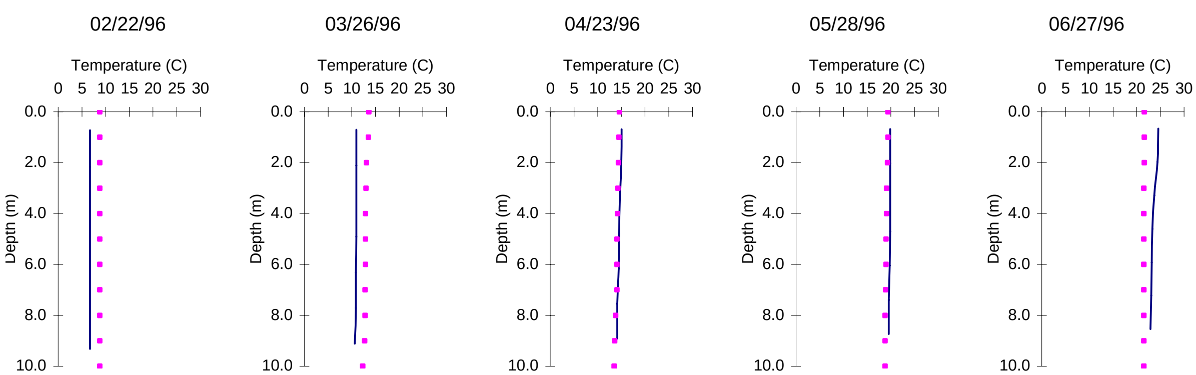


Figure B-6. Temperature calibration results at the Lower Arm (CL3) station (points are observed data, lines are simulated data).

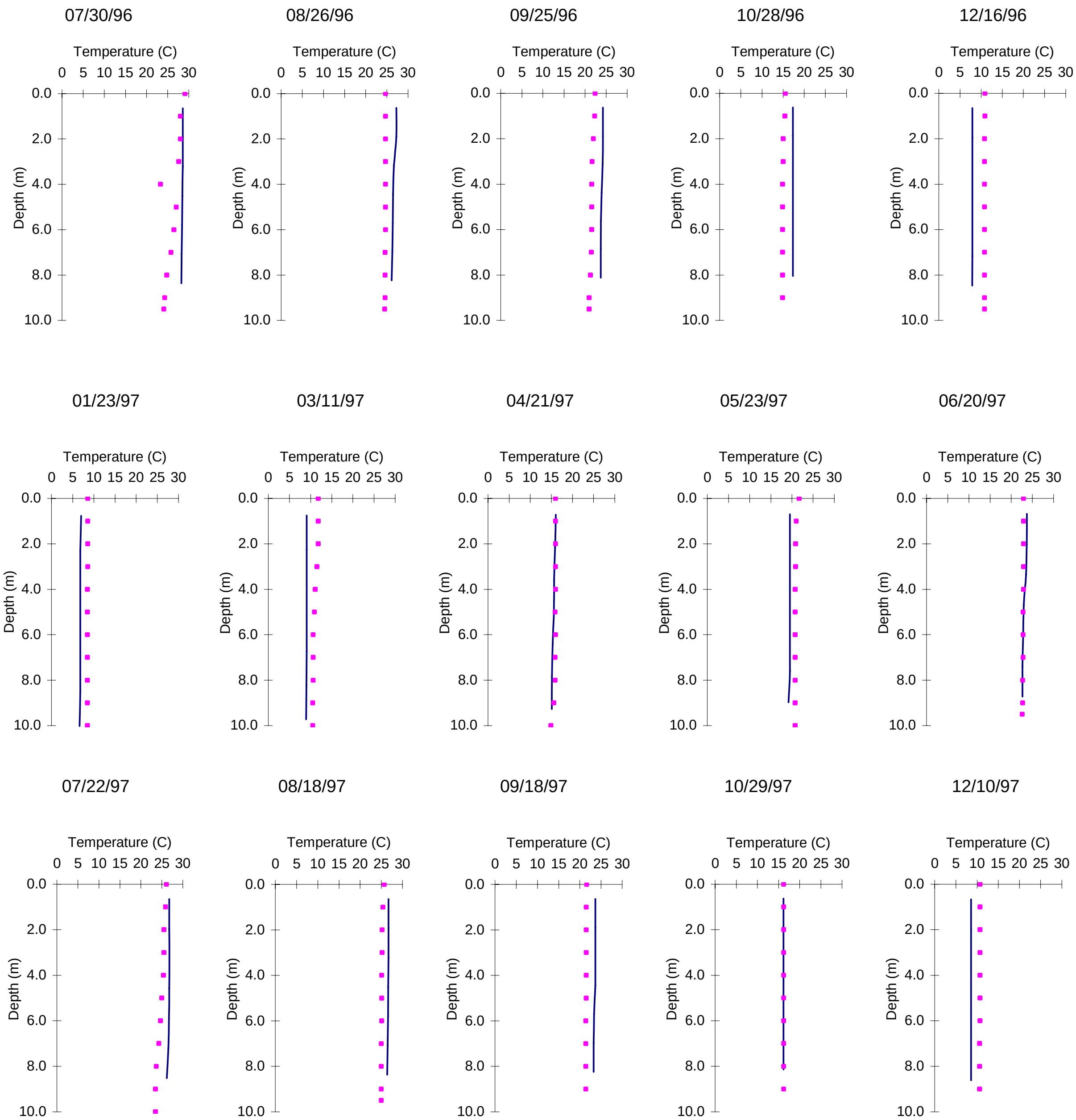


Figure B-6 (continued). Temperature calibration results at the Lower Arm (CL3) station (points are observed data, lines are simulated data).

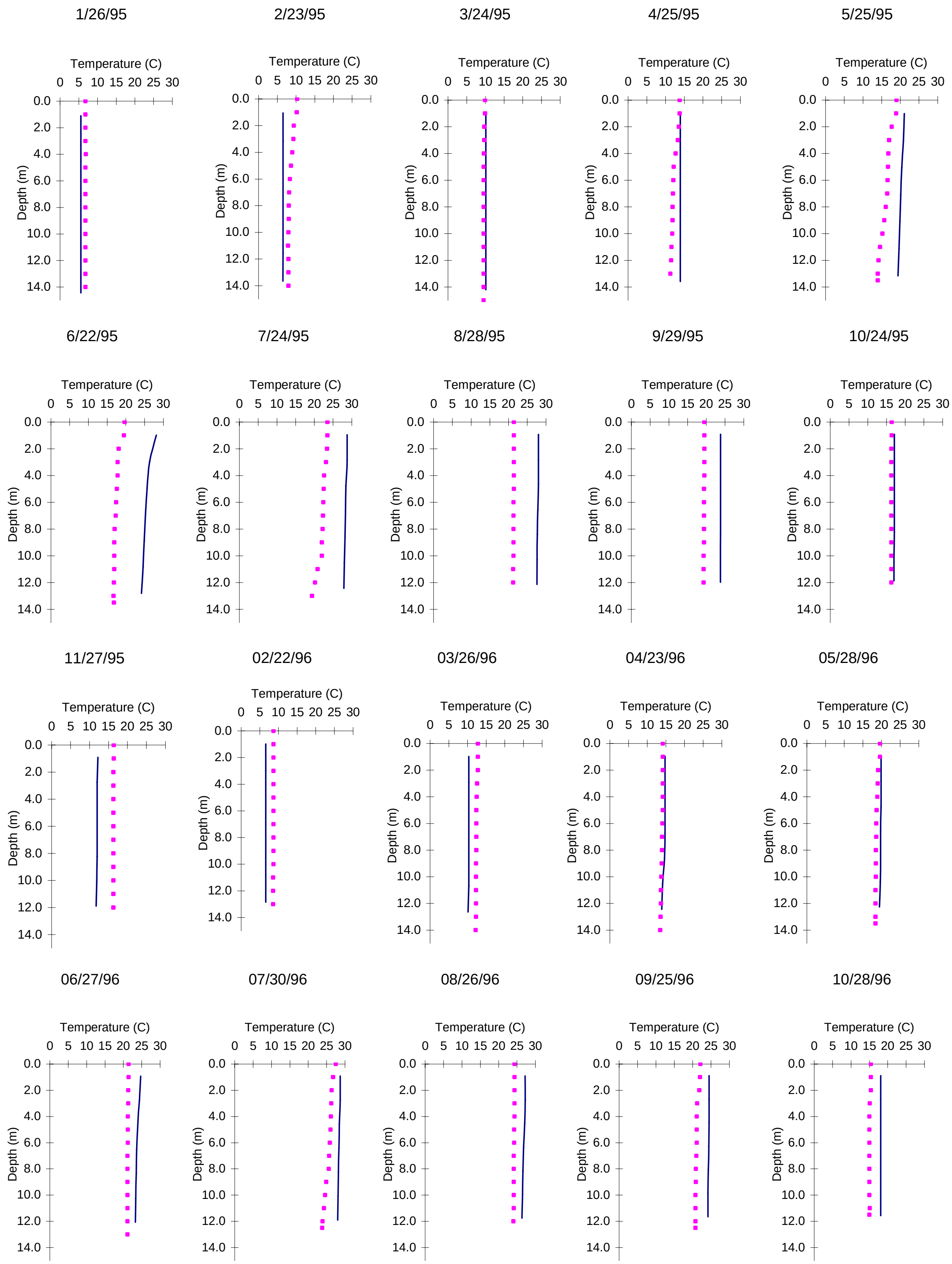


Figure B-7. Temperature calibration results at the Oaks Arm (CL4) station (points are observed data, lines are simulated data).

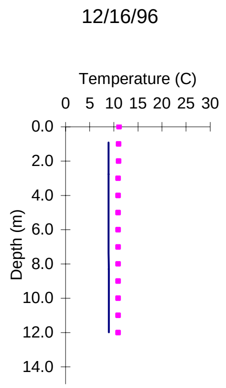


Figure B-7 (continued). Temperature calibration results at the Oaks Arm (CL4) station (points are observed data, lines are simulated data).

APPENDIX C: WATERSHED WATER QUALITY CALIBRATION AND VALIDATION

The following pages present graphs comparing model runs to observed total phosphorus and dissolved orthophosphorus data for the calibration period (October 1, 1992 to September 30, 1993) at two of the three gaged locations in the Clear Lake watershed (Scotts Creek and Middle Creek). Water Quality data from the Kelsey Creek station was not recorded until 1994, so this station was not used in the phosphorus calibration.

Water year 1993 was used for calibration because in addition to water quality sampling data, phosphorus loading from Scotts, Middle, and Kelsey Creeks was calculated for that water year, and provides additional calibration data. Nitrogen data was not collected at Scotts, Middle, or Kelsey Creeks during water year 1993. In-lake water quality was calibrated using the period of January 1st, 1995 to December 31st, 1997. Simulated vs. observed dissolved oxygen results are shown for surface and bottom portions of the water column at stations CL1, CL3, and CL4.

The watershed water quality simulation was validated for the time period of October 1, 1993 to September 30, 1995. Sparse nitrogen data (3 data points) were available from the validation time period. Phosphorus and orthophosphorus data were recorded at all three stations (Scotts, Middle, and Kelsey Creek) during the validation period, and are compared to model results in this appendix.

Although data obtained from local weather stations were used in this modeling effort, localized rainfall events were not always reflected in actual rainfall recorded data. This resulted in discrepancies between modeled and observed water quality data for various storms throughout the calibration and validation time periods.

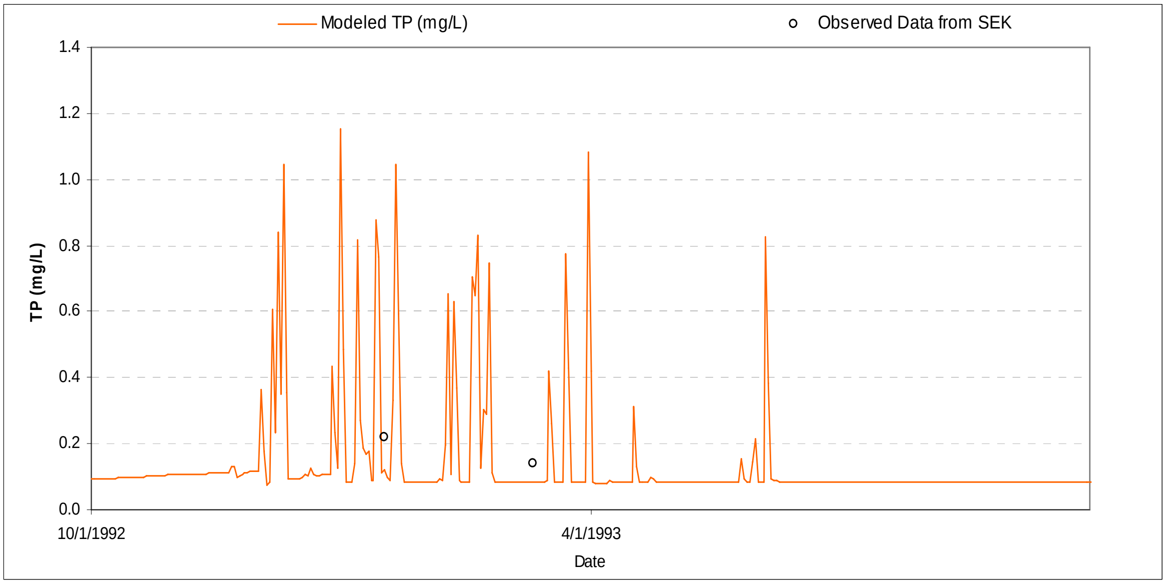


Figure C-1. Total phosphorus calibration results at the Scotts Creek (SEK) gage.

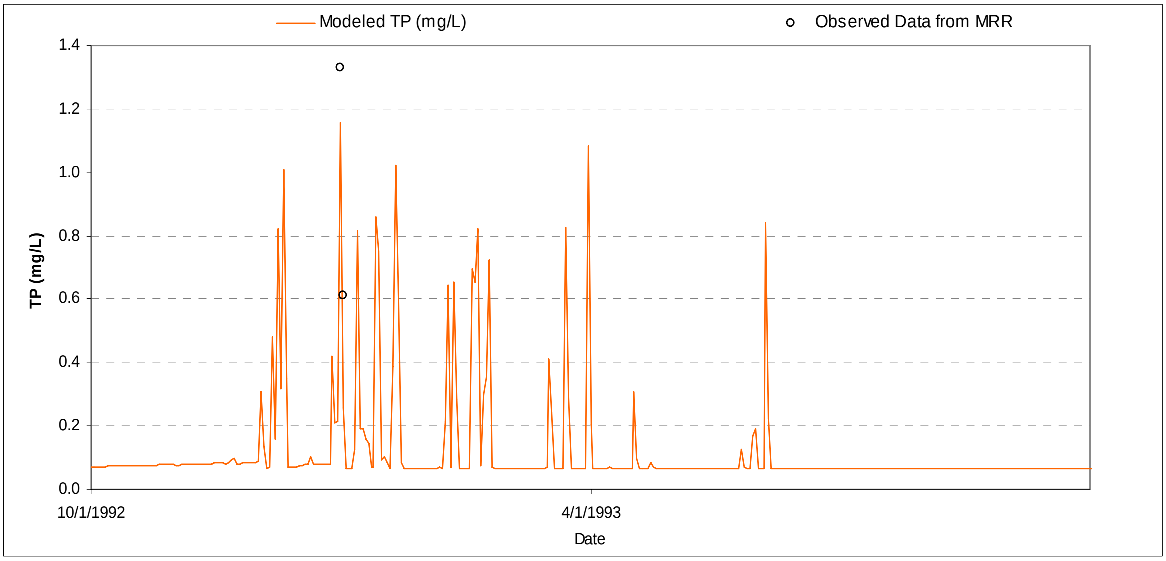


Figure C-2. Total phosphorus calibration results at the Middle Creek (MRR) gage.

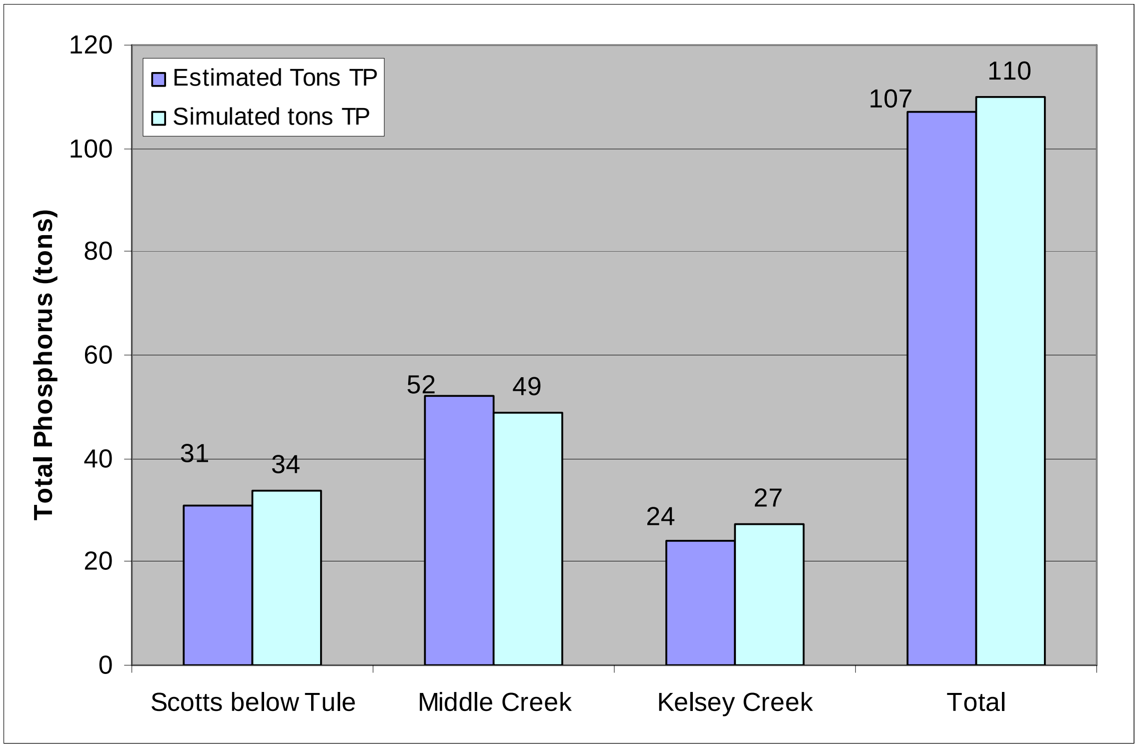


Figure C-3. Total phosphorus loading simulation results for Scotts Creek, Middle Creek, and Kelsey Creek (see Figure C-4), compared to the WY 1993 Watershed Loading study.

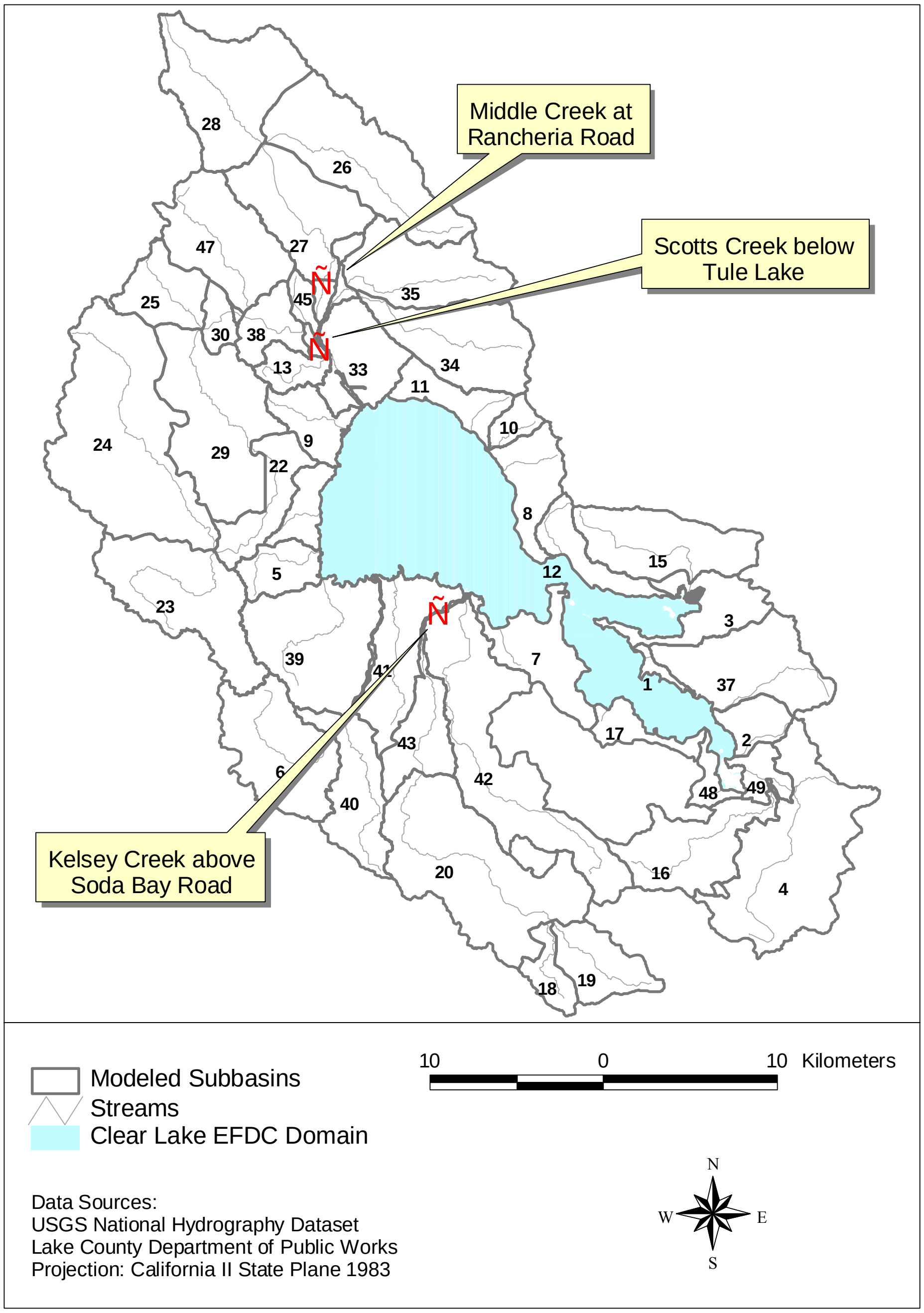


Figure C-4. Total phosphorus loading estimation locations used in the WY 1993 Watershed Loading study.

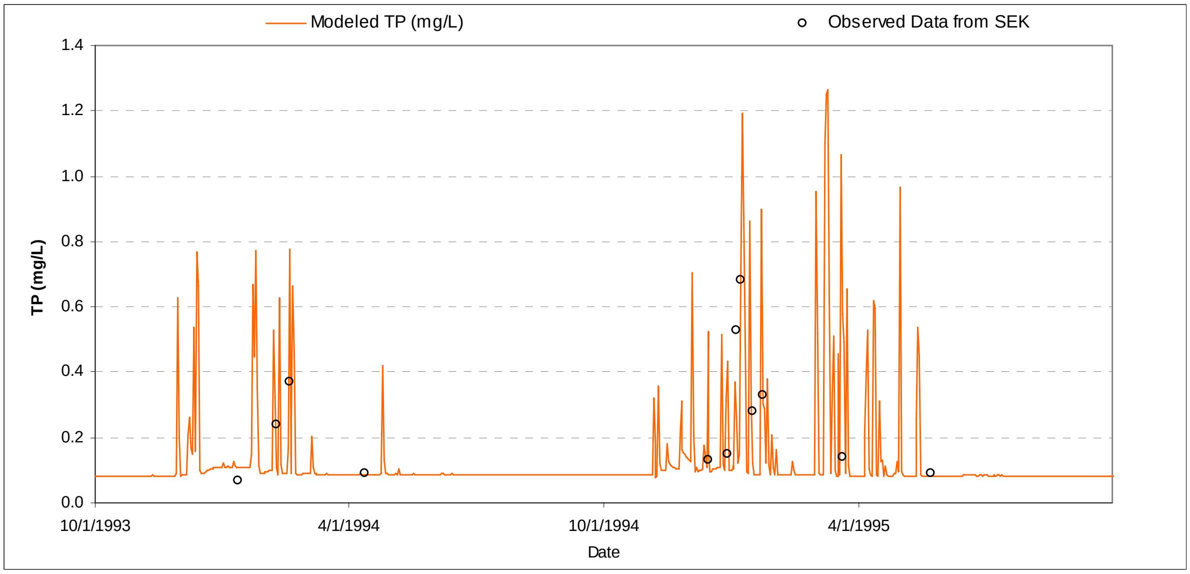


Figure C-5. Total Phosphorus validation results at the Scotts Creek (SEK) gage.

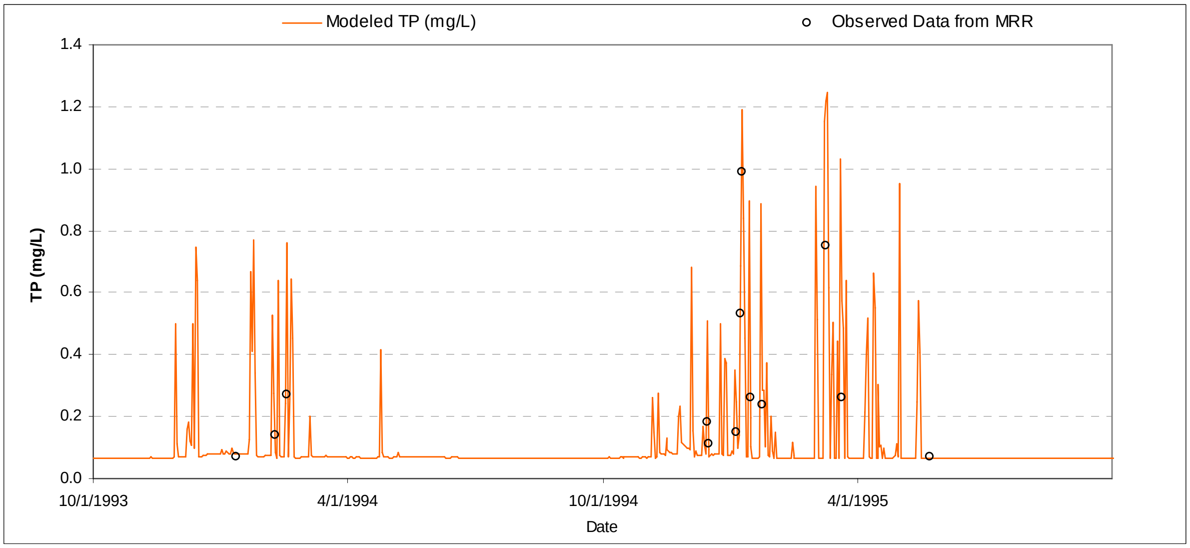


Figure C-6. Total Phosphorus validation results at the Middle Creek (MRR) gage.

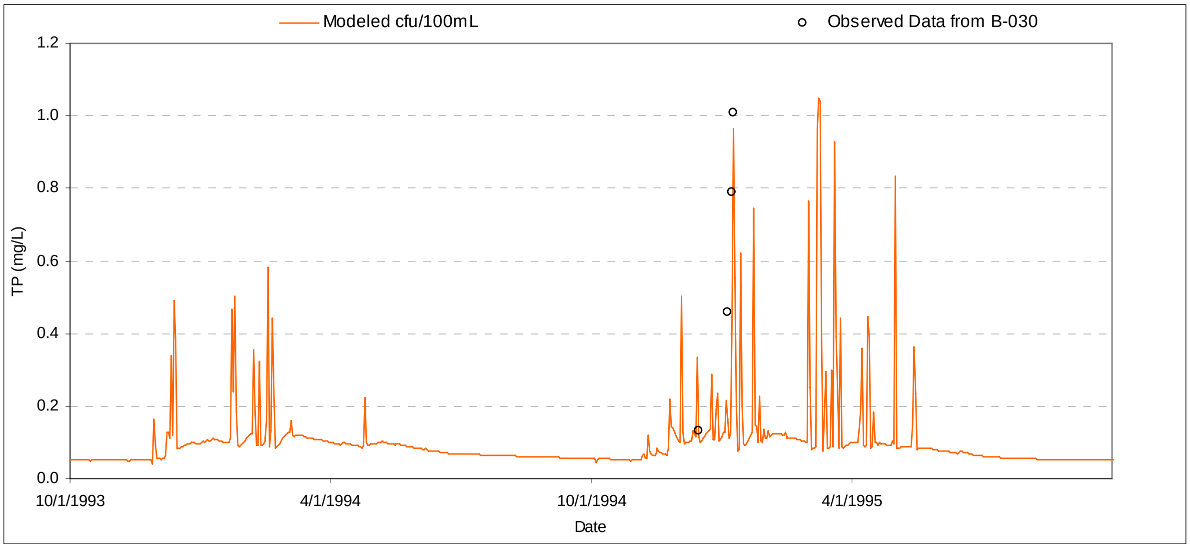


Figure C-7. Total Phosphorus validation results at the Kelsey Creek (KSB) gage.

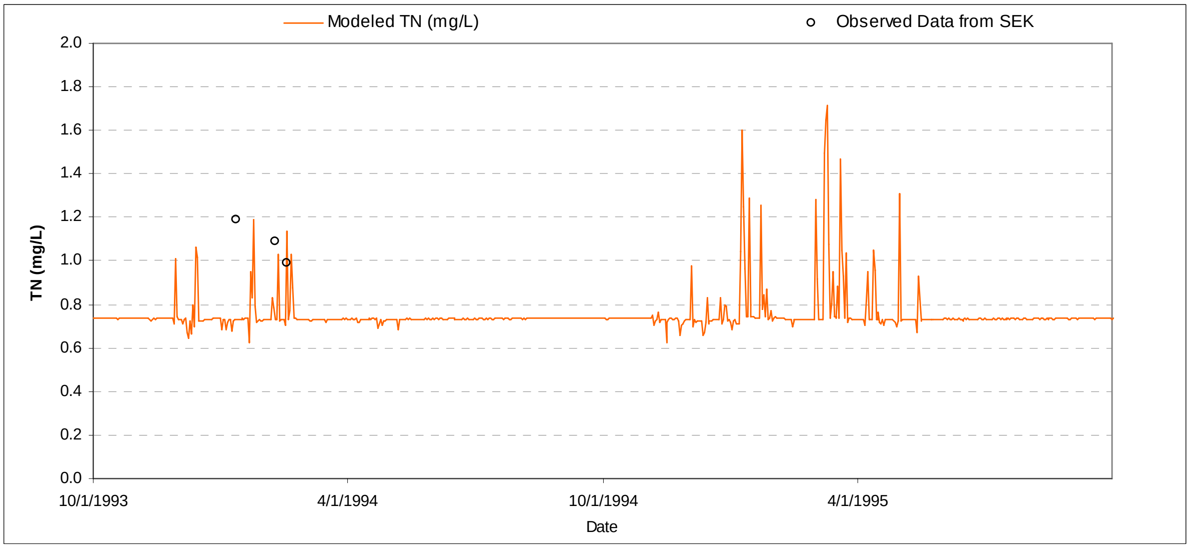


Figure C-8. Total nitrogen calibration/validation results at the Scotts Creek (SEK) gage.

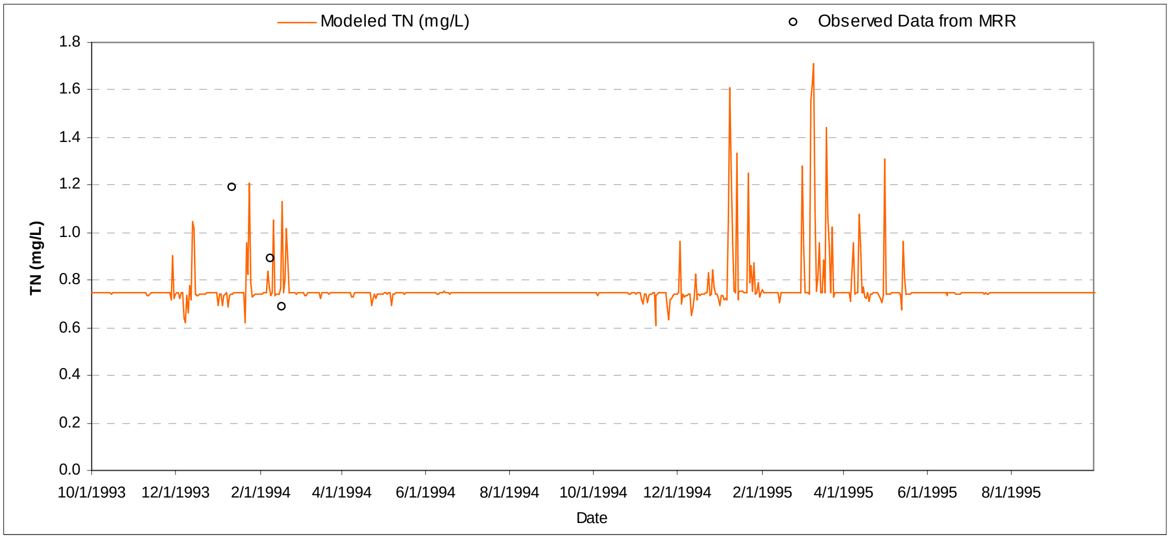


Figure C-9. Total nitrogen validation results at the Middle Creek (MRR) gage.

APPENDIX D: RECEIVING WATER QUALITY CALIBRATION AND VALIDATION

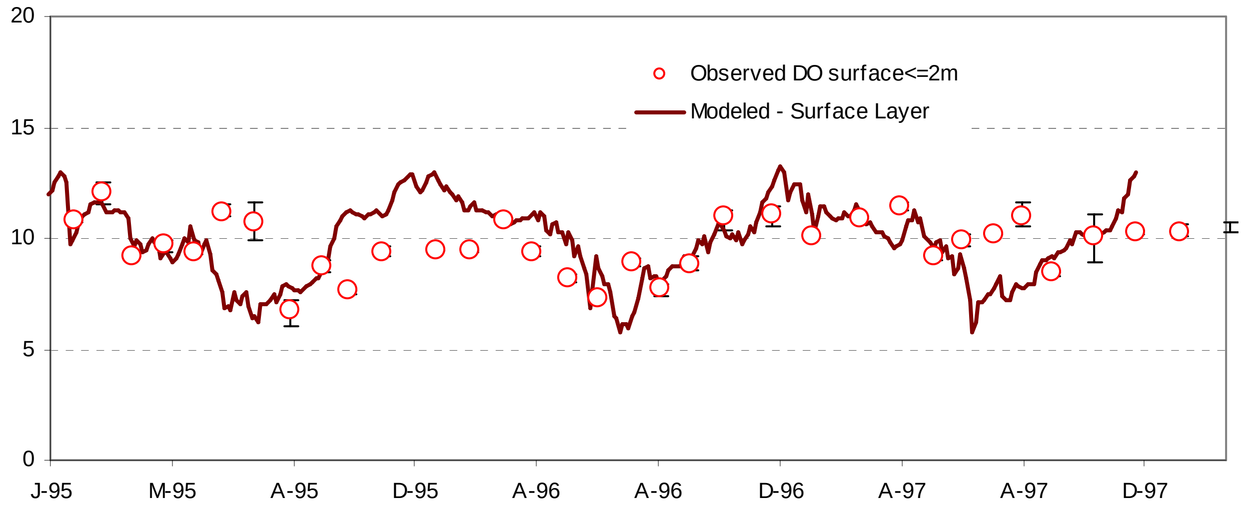


Figure D-1. Dissolved oxygen at the surface layer of the Upper Arm station (CL1).

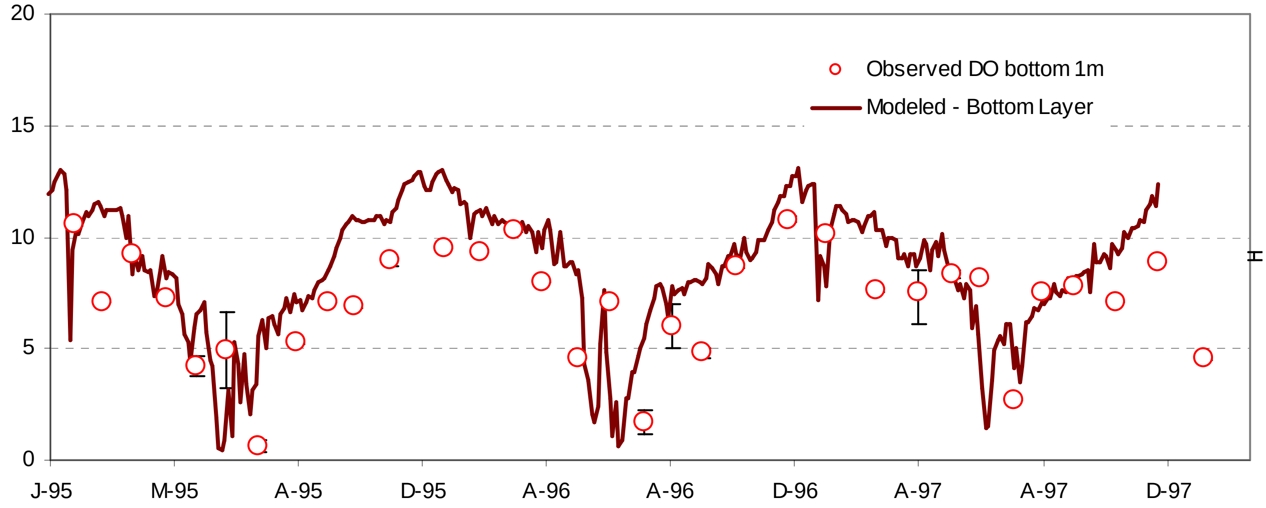


Figure D-2. Dissolved oxygen at the bottom layer of the Upper Arm station (CL1).

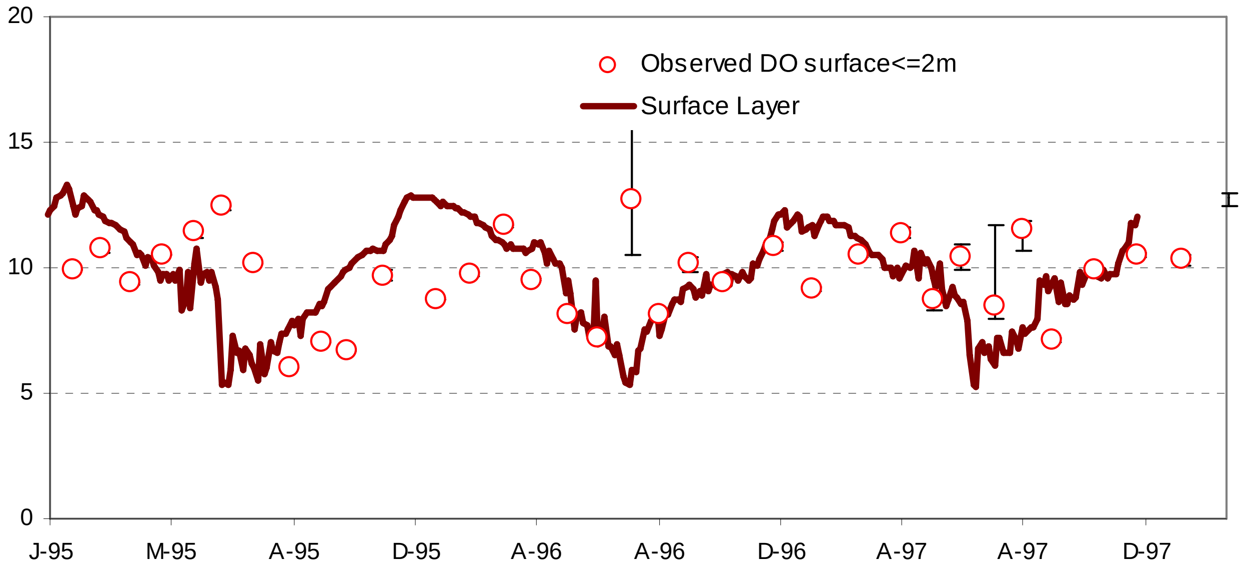


Figure D-3. Dissolved oxygen at the surface layer of the Lower Arm station (CL3).

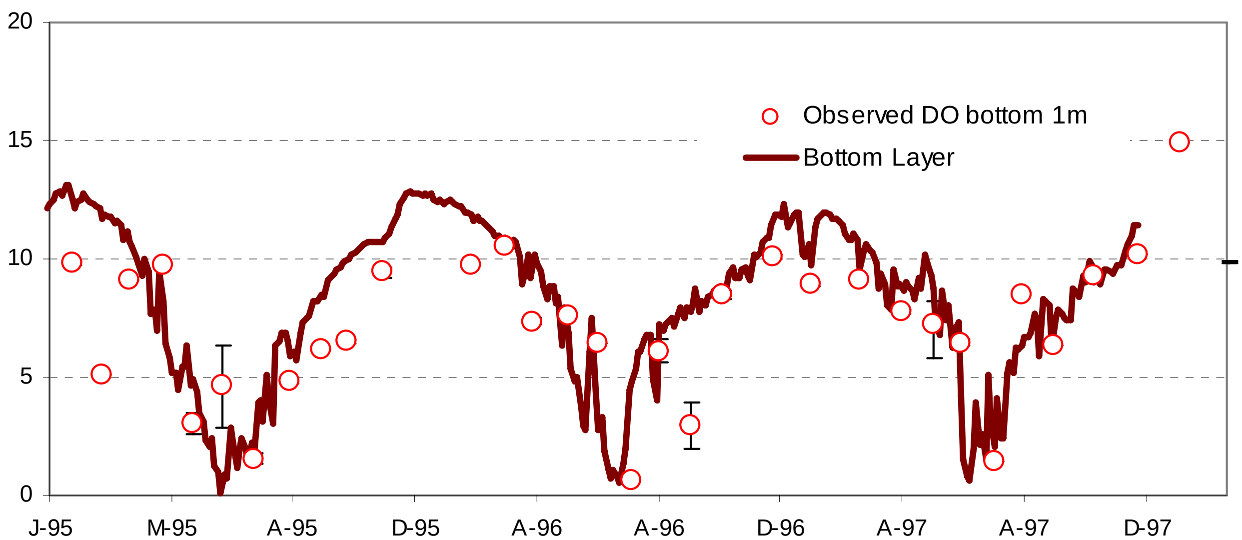


Figure D-4. Dissolved oxygen at the bottom layer of the Lower Arm station (CL3).

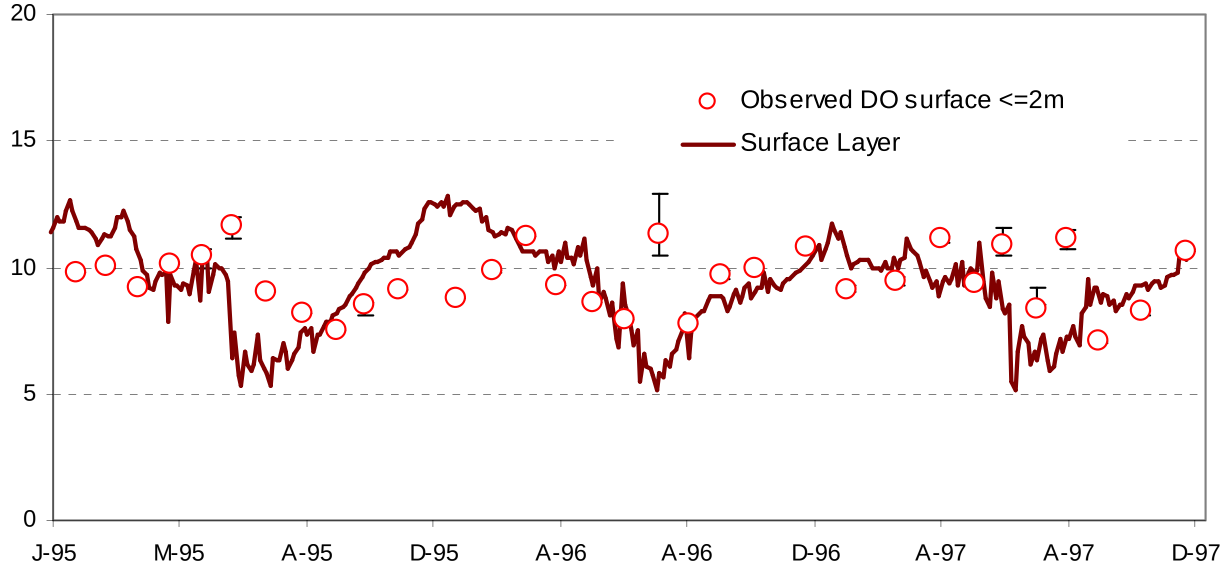


Figure D-5. Dissolved oxygen at the surface layer of the Oaks Arm station (CL4).

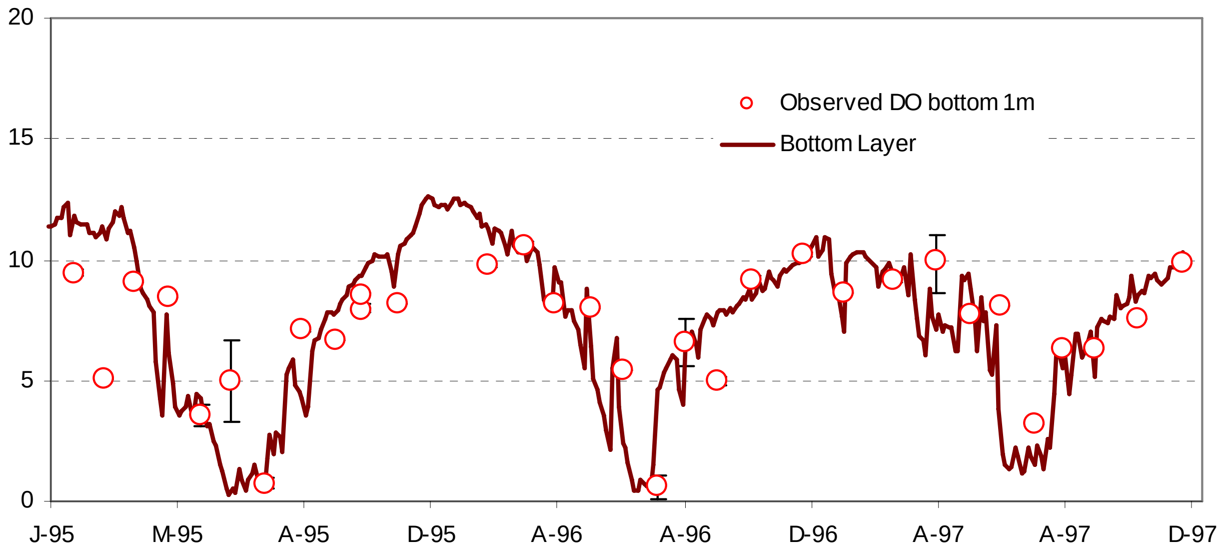


Figure D-6. Dissolved oxygen at the bottom layer of the Oaks Arm station (CL4).

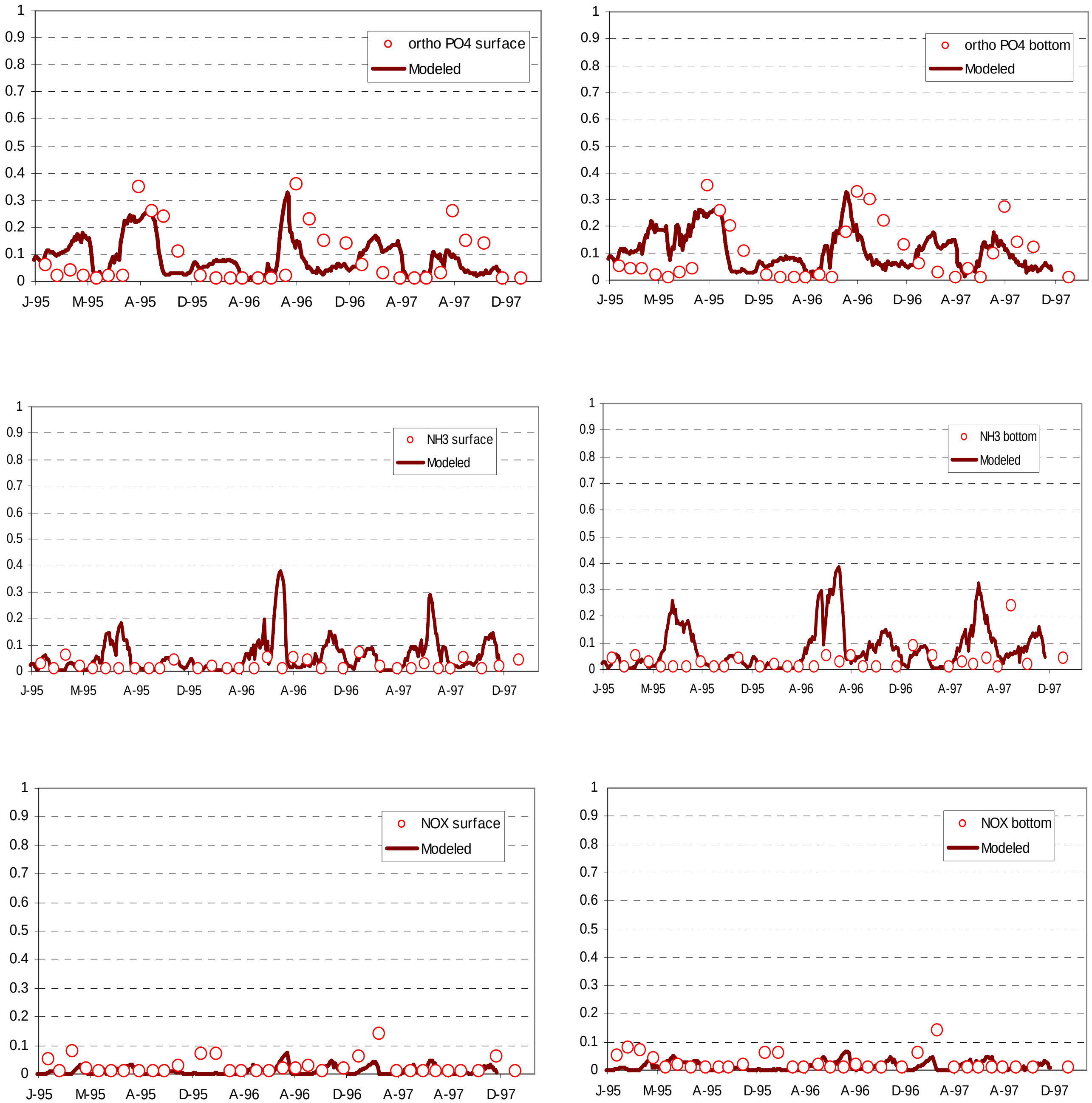


Figure D-7. Surface and Bottom layer plots of orthophosphorus, NH3, and NOx at the Upper Arm station (CL1).

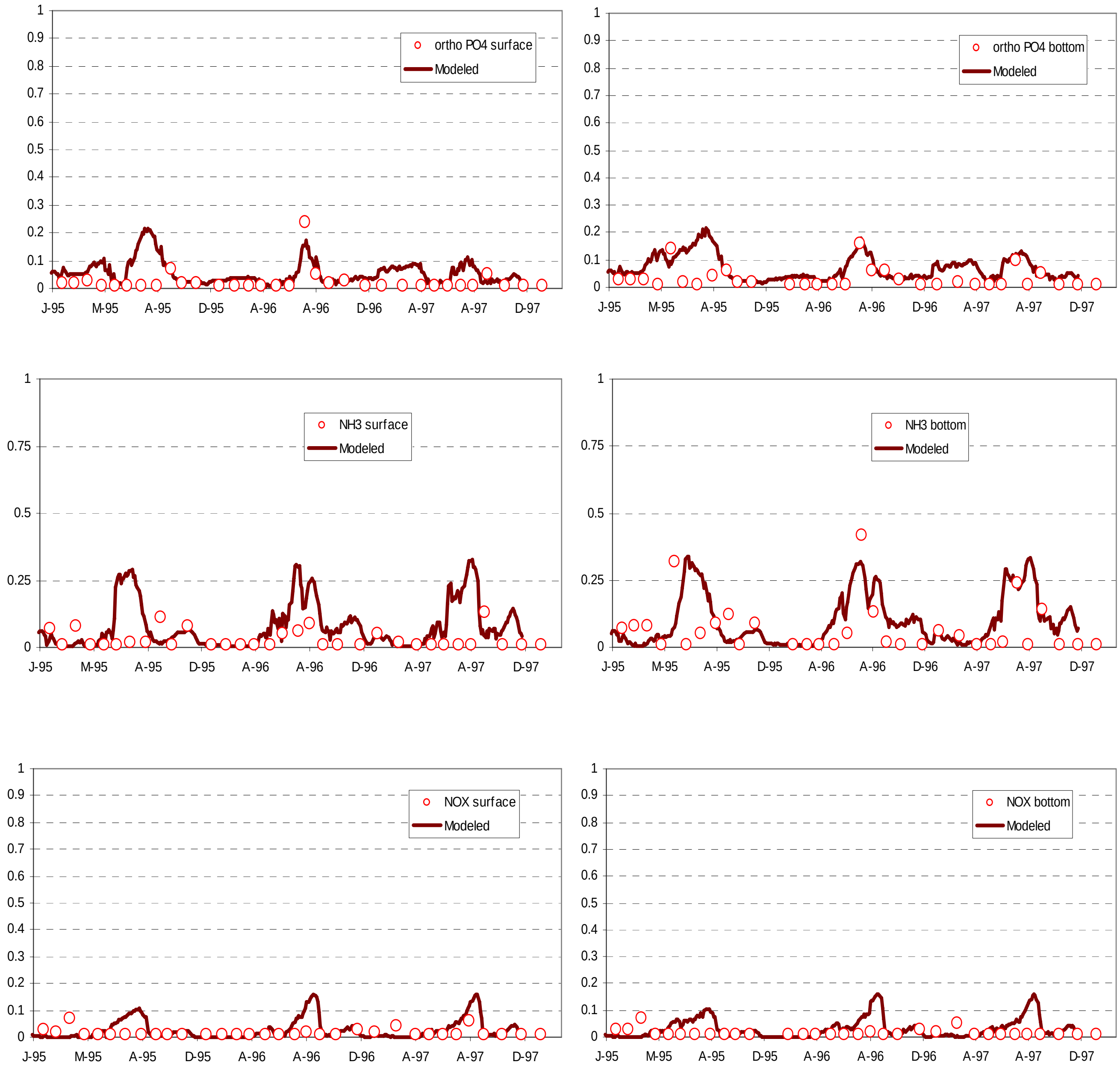


Figure D-8. Surface and Bottom layer plots of orthophosphorus, NH3, and NOx at the Lower Arm station (CL3).

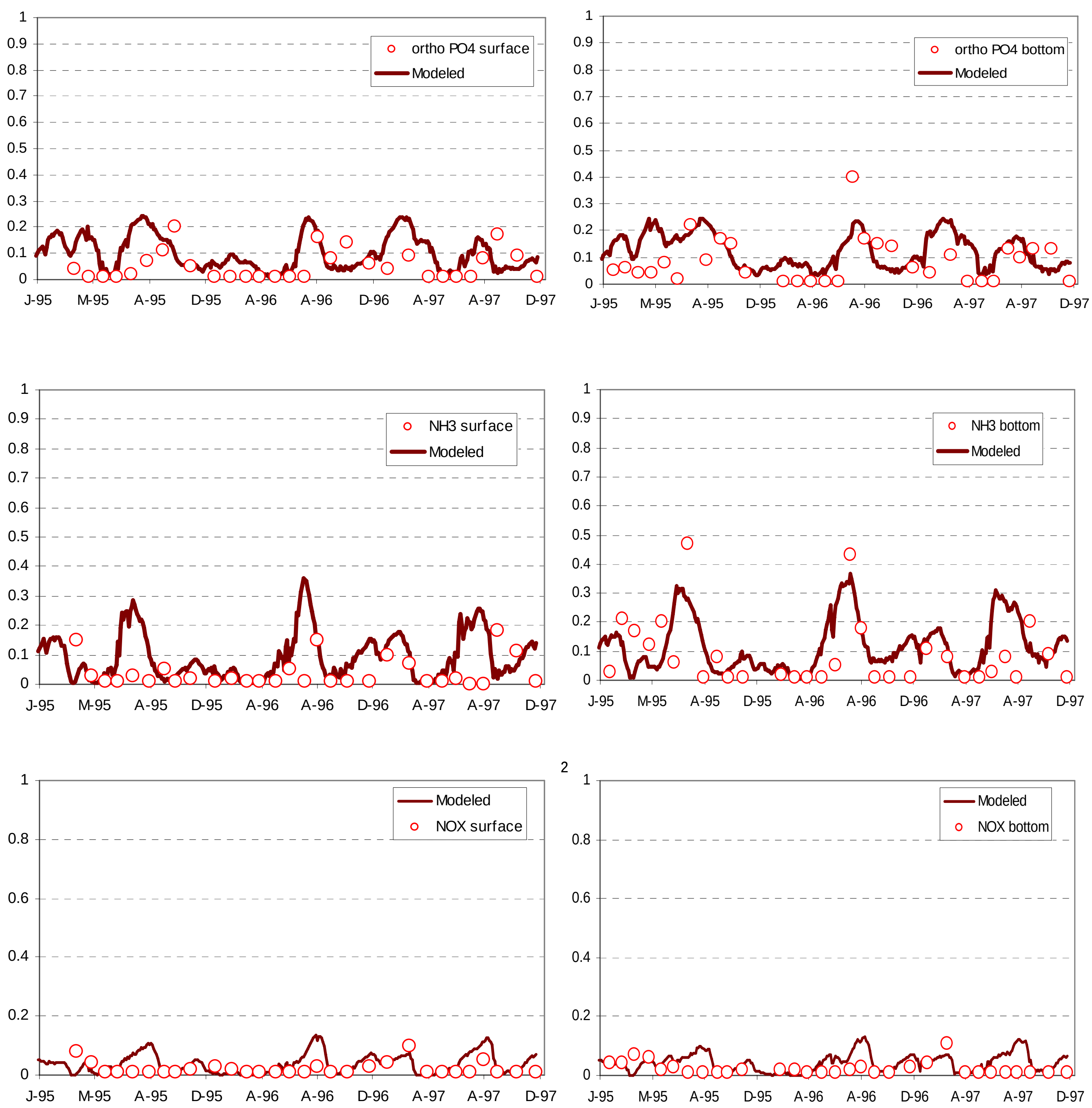


Figure D-9. Surface and Bottom layer plots of orthophosphorus, NH3, and NOx at the Oaks Arm station (CL4).

APPENDIX E: WATER QUALITY DATA ANALYSIS PLOTS

This Appendix discusses and illustrates the regression analyses performed to identify the cause of blue-green algal blooms in Clear Lake. Excess phosphorus loading to the lake is the cause of the blooms, but several sources of phosphorus exist in the system. The following discusses the extent of influence of each source on blue-green algal productivity. Regression analyses between watershed data collected at Scotts Creek (Scotts Creek contributes approximately 30% of the total load of sediments to Clear Lake) and station CL1 in the upper arm of Clear Lake do not suggest a strong relationship between watershed loading and in-lake water quality. A relationship does not exist between watershed runoff inflows and total phosphorus concentration and CL1 ($R^2 = 0.22$ [inverse]) (Figure E-1), or watershed inflows and phytoplankton concentrations (R^2 =

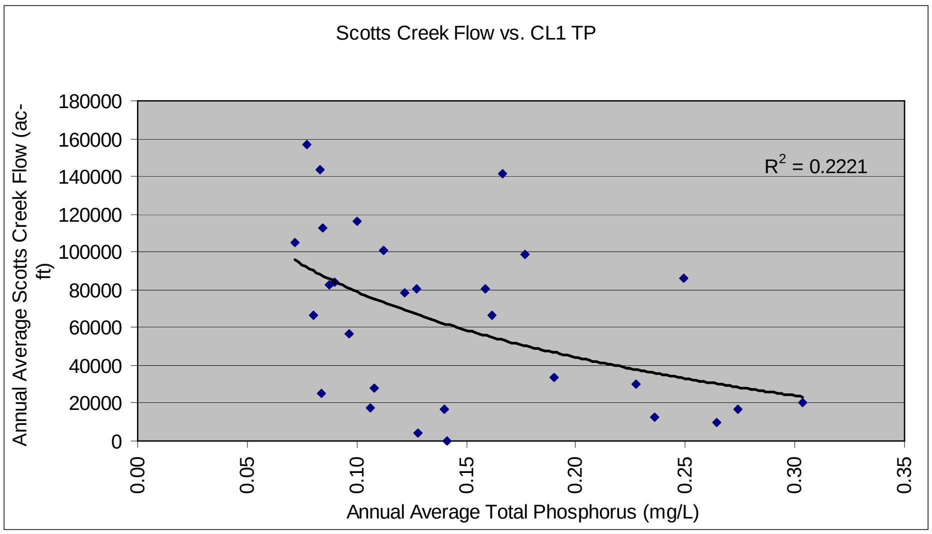


Figure E-1. Logarithmic regression plot of Annual Average Scotts Creek flows vs. total phosphorus concentration at CL1.

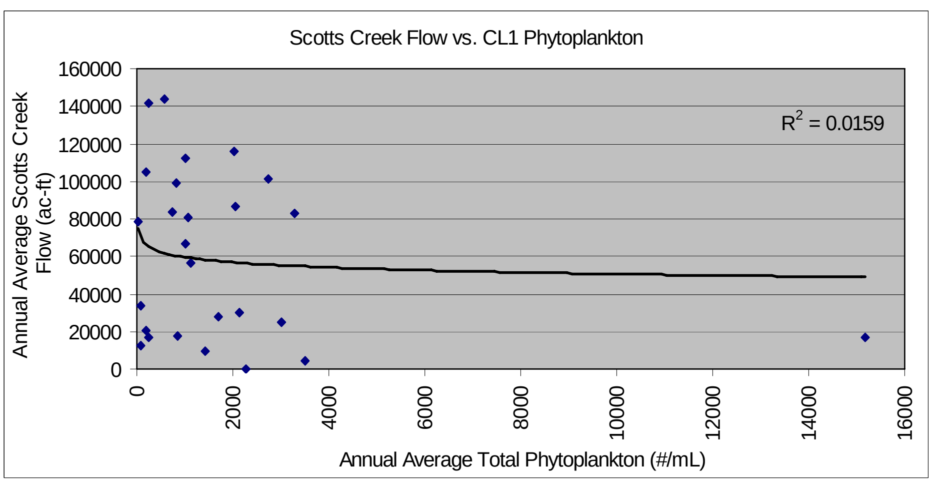


Figure E-2. Logarithmic regression plot of Annual Average Scotts Creek flows vs. total phytoplankton concentration at CL1.

0.02 [inverse]) (Figure E-2). In addition, watershed inflows were not related to in-lake secchi depth (R^2 = 0.04) (Figure E-3). Secchi depths were weakly correlated with total phytoplankton (R^2 = 0.28) (Figure E-4), suggesting that algal biomass rather than sediment from watershed contributions is more influential upon water clarity. Although these relationships were not found to be strong, the fact that total phosphorus shows an inverse relationship with watershed inflow supports the theory that dilution has a dominant influence in Clear Lake.

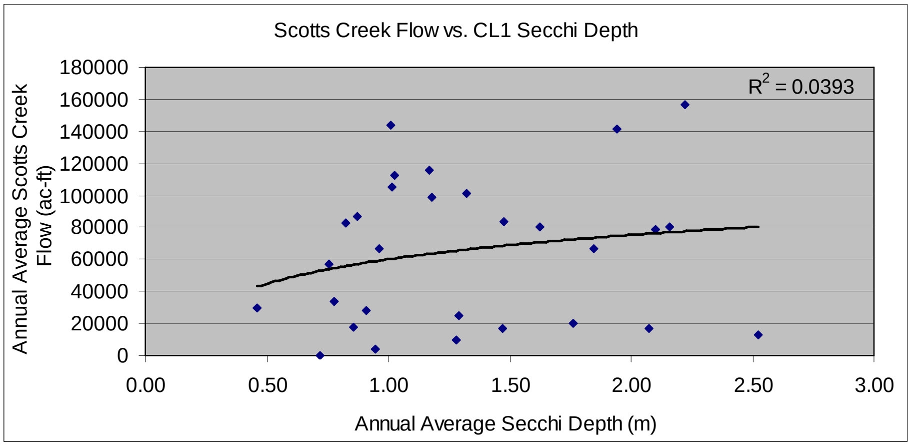


Figure E-3. Logarithmic regression plot of Annual Average Scotts Creek flows vs. Secchi Depth at CL1.

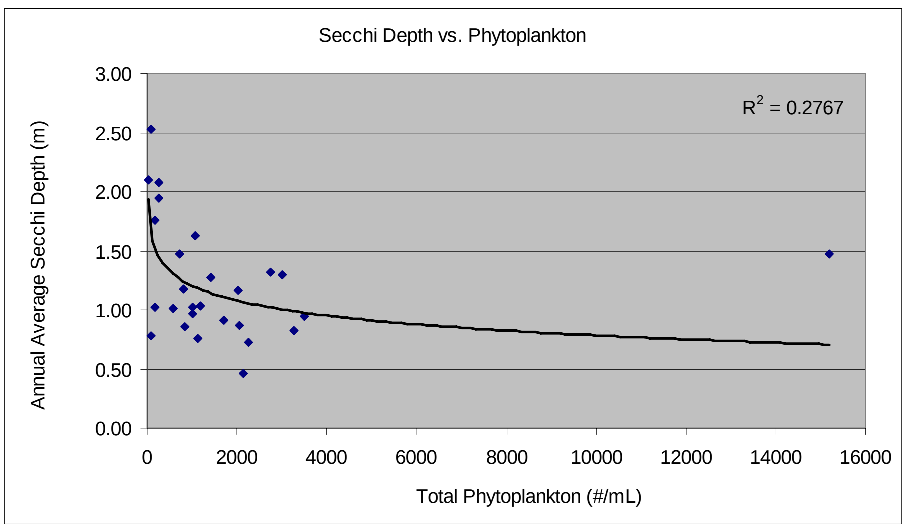


Figure E-4. Logarithmic regression plot of Annual Average Secchi Depth vs. Total Phytoplankton at CL1.